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U. S. DEPARTMENT OF AGRICULTURE
OFFICE OF EXPERIMENT STATIONS
A. W. HARRIS, DIRECTOR

EXPERIMENT STATION BULLETIN No. 8

SIX LECTURES

ON THE

INVESTIGATIONS AT ROTHAMSTED EXPERIMENTAL STATION

DELIVERED UNDER THE PROVISIONS OF

THE LAWES AGRICULTURAL TRUST

BY

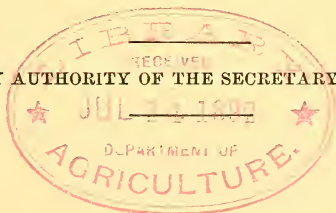
ROBERT WARINGTON, F. R. S.

BEFORE THE

Association of American Agricultural Colleges and Experiment Stations

AT WASHINGTON, D. C., AUGUST 12-18, 1891

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TABLE OF CONTENTS.

	Page.
Lecture I. THE ROTHAMSTED EXPERIMENTAL STATION.	
History of Rothamsted—Commencement of investigations—The field experiments—The wheat crop in Broadbalk field—Mode of conducting field experiments—Investigations respecting plants, rain, and soils—Experiments with animals—The Rothamsted laboratory—Laboratory work—Meteorological work—Publications—The new foundation.....	7-21
Lecture II. THE CIRCUMSTANCES WHICH DETERMINE THE RISE AND FALL OF NITROGENOUS MATTER IN THE SOIL.	
Nature of the nitrogenous matter in soils—Origin of the nitrogenous organic matter: (1) Subsoil nitrogen; (2) surface soil nitrogen—Gains of nitrogen in soil: (1) Gains in pasture; (2) gains in clover land; (3) gains in a four-course rotation; summary—Sources of the nitrogen in surface soils: (1) Nitrogen from subsoil; (2) ammonia and nitrates from the air; (3) free nitrogen from the air—Limits to the accumulation of nitrogen—Losses of nitrogen—Influence of crop residues—Causes which determine loss of nitrogen—Tendency to equilibrium in soils—Rothamsted method of sampling soil	22-41
Lecture III. NITRIFICATION.	
Natural sources of nitrates—Artificial production of niter—Former theories of nitrification—Appearance of nitrous acid in bodies exposed to air—Nitrification produced by a living organism—Conditions necessary for nitrification—Substances capable of nitrification—Products of nitrification—The isolation of the nitrous organism	42-59
Lecture IV. NITRIFICATION AND DENITRIFICATION.	
The separation of the nitric organism—Properties of the nitric organism—Present theory of nitrification—Denitrification—Distribution of the nitrifying organism in soil—Determination of nitrates in soil—Rates of nitrification in soil: (1) Laboratory experiments; (2) results with field soils; (3) the Rothamsted drain gauges	60-76
Lecture V. NITRIFICATION OF SOILS AND MANURES.	
Production of nitrates in uncropped soils throughout the year—Nitrates in cropped soils—Use of crops to prevent loss of nitrates—Nitrates in soils cropped and manured—Nitrification of manures.....	77-94
Lecture VI. DRAINAGE AND WELL WATERS.	
Movements of salts within the soil—Drainage by open channels and by displacement—The substances removed in drainage water—Alterations in composition at different seasons—The deep well waters of Harpenden: (1) Uncontaminated wells; (2) Contaminated wells; (3) Mineral constituents of the water—Conclusion.....	95-112

LIST OF ILLUSTRATIONS.

	Page.
PLATE I. Portrait of Sir J. B. Lawes, Bart	Frontispiece
II. Rothamsted Manor House.....	8
III. Map of Rothamsted.....	10
IV. Wheat grown at Rothamsted.....	14
V. Rothamsted laboratory.....	18
VI, VII. Nitrous organisms	58
VIII. Fig. 1. Nitric organisms	60
Fig. 2. Denitrifying organism.....	60
IX. Chart showing nitrates in drainage water from an unmanured bare soil	78
X. Chart showing chlorine in Harpenden well waters.....	108
XI. Chart showing nitrates in Harpenden well waters	108

LETTER OF TRANSMITTAL.

U. S. DEPARTMENT OF AGRICULTURE,
OFFICE OF EXPERIMENT STATIONS,
Washington, D. C., December 23, 1891.

SIR: I have the honor to transmit herewith for publication Experiment Station Bulletin No. 8 of this Office, containing the lectures on the Investigations at Rothamsted Experimental Station, delivered under the provisions of the Lawes Agricultural Trust, by Robert Warington, F. R. S., before the Association of American Agricultural Colleges and Experiment Stations, at Washington, D. C., August 12-18, 1891. Mr. Warington makes the following statement regarding the personal interest shown by Sir John Bennet Lawes in this course of lectures:

It may, I think, be of interest to the readers of these lectures to know that they were all read by Sir J. B. Lawes before their delivery, and that I had while preparing them the advantage of his kindly and careful criticism. The lecture upon soil (Lecture II) and the notice of some of the results in Broadbalk wheat field in Lecture I were written at his request. He very kindly allowed the use of some hitherto unpublished results, and provided many of the photographic illustrations used in the lectures.

Regarding these lectures the Association unanimously adopted the following resolution:

Resolved, That this Association renew its expression of sincere thanks to Sir John Bennet Lawes for his munificent provision for a course of lectures on the work done at Rothamsted, to be delivered biennially in the United States; and that it also wishes to express its sincere thanks to Mr. R. Warington for consenting to deliver the first series of lectures, and its appreciation of the high scientific and practical value of the course delivered at this meeting.

The distribution of this valuable contribution to the literature of scientific investigations in agriculture as a publication of this Department, will doubtless afford much satisfaction both to those who were privileged to listen to the lectures as originally delivered and to a wide circle of readers who have followed with interest such reports of the researches at Rothamsted as have fallen into their hands.

Respectfully,

A. W. HARRIS,
Director.

Hon. J. M. RUSK,
Secretary of Agriculture.

LECTURE I.

THE ROTHAMSTED EXPERIMENTAL STATION.

History of Rothamsted—Commencement of investigations—The field experiments—The wheat crop in Broadbalk field—Mode of conducting field experiments—Investigations respecting plants, rain, and soils—Experiments with animals—The Rothamsted laboratory—Laboratory work—Meteorological work—Publications—The new foundation.

In commencing my lectures to you I should in the first place say a few words as to the circumstances which have led to these lectures being given. The agricultural experiments which Sir John Bennet Lawes has conducted at Rothamsted during the last fifty years are known throughout the civilized world, but perhaps in no country have they been more appreciated than in America. The results of these experiments are frequently discussed in your agricultural journals. Many of your countrymen on coming to England have visited Rothamsted, inspected the experiments in progress, and made a personal acquaintance with Sir John Lawes. The friendly intercourse which has been established has led to Sir John himself becoming a writer in several of your agricultural periodicals. It is the desire of Sir John Lawes that this friendly intercourse should not cease, and in drawing up the trust deed, by which provision is made for the continuance of the Rothamsted experiments, he has instituted a course of lectures to be delivered biennially in the United States upon the investigations and experiments carried out in the laboratory and upon the land of the Rothamsted Experimental Station. His object in doing this is, as I have heard him say, that Americans should feel that "they have a share" in any benefits which may arise from the Rothamsted endowment.

The deed of foundation, by which Rothamsted passed under its new management, was executed in February, 1889. In June of last year the managing committee requested me to deliver the first course of lectures in America. A difficulty at once arose as to where these lectures should be given. The centers in the United States at which lectures such as these would be appropriate are so numerous and the distances between them so great that the task of reaching the desired audience of scientific agriculturists seemed almost hopeless. Our difficulties have most fortunately been solved by your Association. Your willingness to receive these lectures at your annual meeting has saved many journeys through the States and has given me the great pleasure and advantage of addressing at one time representative men in agricultural science gathered from the greater part of your vast country.

With this brief introduction I must now turn to the special subject of my lecture. As this is the first lecture you have received upon the subject of Rothamsted I have thought it best to commence by giving you some account of the place and of the work done there.

HISTORY OF ROTHAMSTED.

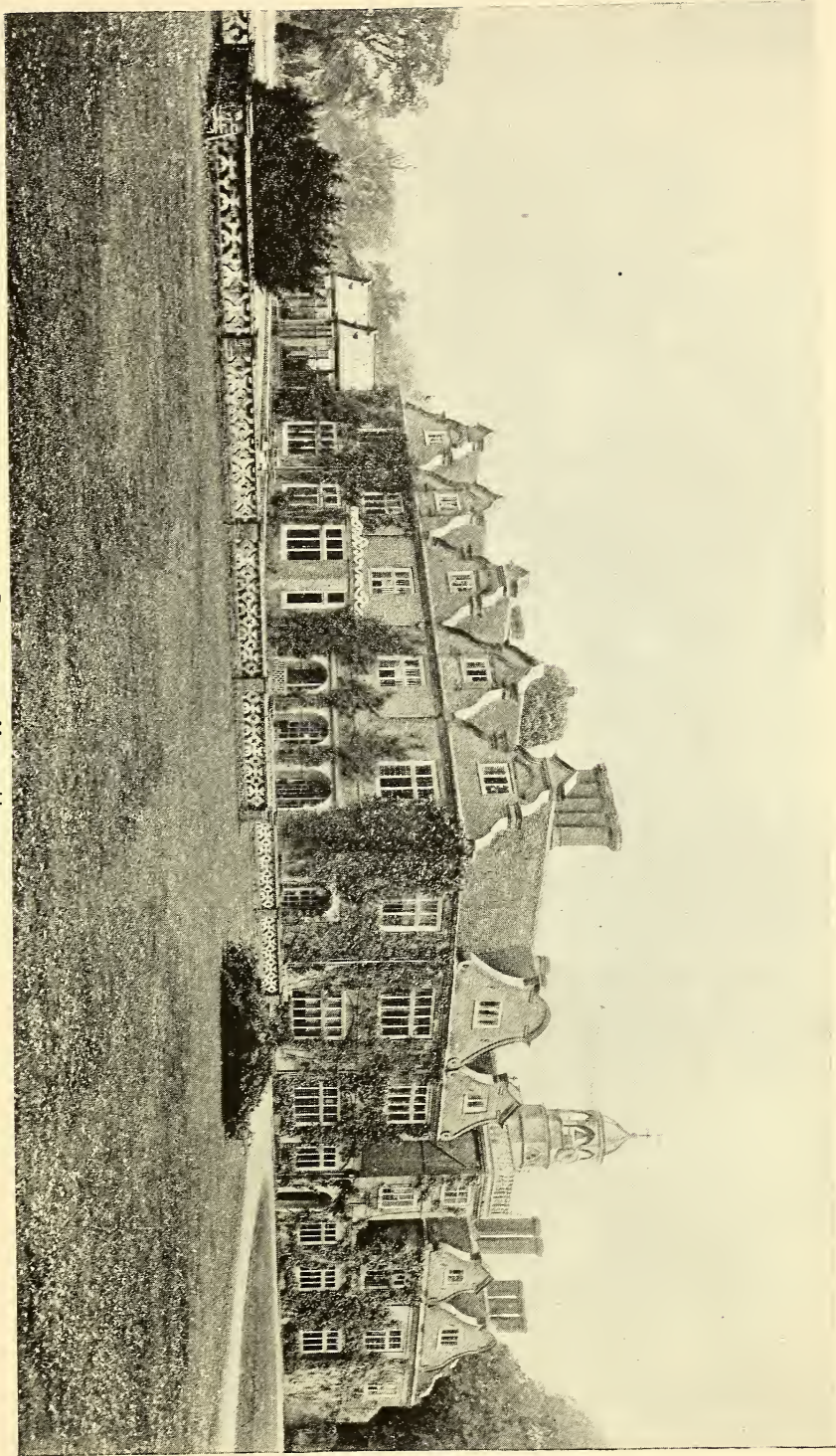
The manor of Rothamsted adjoins and includes a considerable part of the parish of Harpenden in Hertfordshire; it lies about 25 miles north of London and about 4 miles north of the city of St. Albans. The manor has been held successively by several families. It came into the hands of the present family in the year 1623.

Sir John Bennet Lawes is descended from the family of Wittewronge. About the year 1564 Jaques Wittewronge came to England from Flanders, being induced to take this step from the religious persecution then prevailing. The family first settled at Stantonbury, Buckinghamshire. In 1623 the manor of Rothamsted was purchased from the owner, Bardolf, for John Wittewronge, who was then a minor. He was created a knight and afterwards a baronet by Charles II. In the absence of male heirs the baronetcy ceased to exist, and the Lawes family succeeded to the estate by marriage with Mary Bennet, great granddaughter of James Wittewronge. John Bennet Lawes, the first of the name, died in 1822, and was succeeded by his son, the present owner of Rothamsted, born in 1814. Mr. John Bennet Lawes was educated at Eton and afterwards at the University of Oxford. He entered into the possession of Rothamsted in 1834. The work he has since accomplished there will form the subject of these and I trust of many future lectures. In recognition of his great services to agriculture he was created a baronet in 1882. The portrait of Sir John Lawes selected for reproduction in the published volume of these lectures shows him as he appears at the present time. (Plate I, frontispiece.)

The house of Rothamsted was built many years before the coming of the Wittewronges to England; it dates according to Cussan's History of Hertfordshire, from about the year 1470. It was thus in existence before the discovery of America by Columbus. The front had originally four pointed gables, two on each side of a low central tower. Sir John Wittewronge after purchasing the property rounded these gables and extended the front somewhat at each end; he also placed a clock turret on the central tower. The front remains at present as it was left by him in 1650, but Sir John Lawes has considerably extended one side of the house, preserving the character of the old building. (Plate II.)

COMMENCEMENT OF INVESTIGATIONS.

It is always interesting to trace the beginnings of any important work. On the subject of Rothamsted work I think I can not do better than read to you two paragraphs from an autobiographical note written by



ROTHAMSTED MANOR HOUSE.

Sir John Lawes three years ago, at the request of Mr. Morton, the editor of the *Agricultural Gazette* (*Agricultural Gazette*, January 2, 1888).

DEAR MR. MORTON: In answer to your inquiries, it is always difficult to predict whether a juvenile taste will develop in after life into anything useful. To write upon the door of a dark room with a stick of phosphorus, to dissolve a penny in nitric acid, or to convey an electric shock to your old housekeeper, who "refused to touch the jar with her hand, but did not mind touching it with the end of the poker," these are feats which, with the accompanying destruction of clothes and furniture, cause the elders of the house to look with unfavorable eyes at a boy with a taste for chemistry. In my day Eton and Oxford were not of much assistance to those whose tastes were scientific rather than classical, and consequently my early pursuits were of a most desultory character. Matters, however, began to look serious when at the age of twenty I gave an order to a London firm to fit up a complete laboratory; and I am afraid it sadly disturbed the peace of mind of my mother to see one of the best bedrooms in the house fitted up with stoves, retorts, and all the apparatus and reagents necessary for chemical research. At the time my attention was very much directed to the composition of drugs. I almost knew the *Pharmacopœia* by heart, and I was not satisfied until I had made the acquaintance of the author, Dr. A. T. Thomson.

The active principle of a number of substances was being discovered at this time, and in order to make these substances I sowed on my farm poppies, hemlock, henbane, colchicum, belladonna, etc. Some of these are still growing about the place. Dr. Thomson had suggested a process for making calomel and corrosive sublimate by burning quicksilver in chlorine gas. I undertook to carry out the process on a large scale and wasted a good deal of time and money on a process which was in fact no improvement on the process then in use. Failures, however, have their value, as I found out afterwards. All this time I had the home farm, of about 250 acres, in hand. I entered upon it in 1834. Farmers were suffering from the abundance of the crops, and wheat, though rigidly protected, was very low in price. For three or four years I do not remember that any connection between chemistry and agriculture passed through my mind; but the remark of a gentleman (Lord Daere), who farmed near me, who pointed out that on one farm bone was invaluable for the turnip crop, and on another farm it was useless, attracted my attention a good deal, especially as I had spent a good deal of money on bone without success. Somewhere about this time a drug broker in the city of London asked me whether I could make any use of precipitated gypsum and spent animal charcoal, both of which substances held at the time no market value. Some tons of these were sent down, and as sulphuric acid was largely used by me in making chlorine gas, the combination of the two followed.

In 1837, 1838, and 1839 experiments on the effect of various manures were carried out by Mr. Lawes in pots. It was in these trials that the excellent results obtained by manuring turnips with phosphates, previously treated with sulphuric acid, were first observed. These led to experiments of the same kind in the field in 1840 and 1841, and finally to the taking out of a patent in 1842 for treating mineral phosphates with sulphuric acid, which formed the commencement of the present enormous manufacture of artificial manures. During these early experiments an old barn (now pulled down) was employed as a laboratory, and Mr. Lawes had the assistance of a young chemist, Mr. Dobson. The earliest published results appeared in the *Gardener's Chronicle*.

The publication of Liebig's first work on agricultural chemistry, in 1840, gave a great impetus to these investigations and influenced considerably the direction which they took.

It was in the summer of 1843 that Dr. J. H. Gilbert became the chemist at Rothamsted. He had previously been a pupil of Liebig and assistant to Dr. A. T. Thomson. Since 1843 Dr. Gilbert has had a large share in the conduct of the experiments and is responsible for most of the published reports.

The foundation of the Rothamsted Station for agricultural experiments is earlier than that of any other, with the single exception of that established by Boussingault at Bechelbronn in Alsace. The earliest German station, that at Möckern, was founded in 1852; the earliest American station, at Middletown, Connecticut, in 1875.

I must now try to give you a general idea of the work which has been carried on at Rothamsted. The sketch will necessarily be extremely brief and imperfect from the largeness of the subject. I will speak first of the field experiments.

THE FIELD EXPERIMENTS.

It may interest you to know that Sir John Lawes has in his possession an old map of the farm, dated 1623. The fields have now for the most part the same boundaries as they had then and many of them bear the old names. The map of Rothamsted I now show you is a photograph of the ordnance survey of 1877-78. Upon it I have marked the names of the experimental fields. (Plate III.)

The earliest of the systematic field experiments were those with turnips, commencing in 1843. The continuous wheat experiments commenced in the autumn of the same year, the first harvest being in 1844. The experiments with beans, peas, and tares commenced in 1847; those with a four-course rotation in 1848; those with clover in 1849; the alternate wheat and fallow in 1851; the continuous barley in 1852; the permanent grass in 1856; oats in 1869; sugar beet in 1871; and mangel-wurzel and potatoes in 1876. The table before you shows the duration of each experiment and the area under crop. The area of land at present occupied by experimental crops is about 39 acres.

TABLE I.—*Systematic field experiments at Rothamsted, 1843-91.*

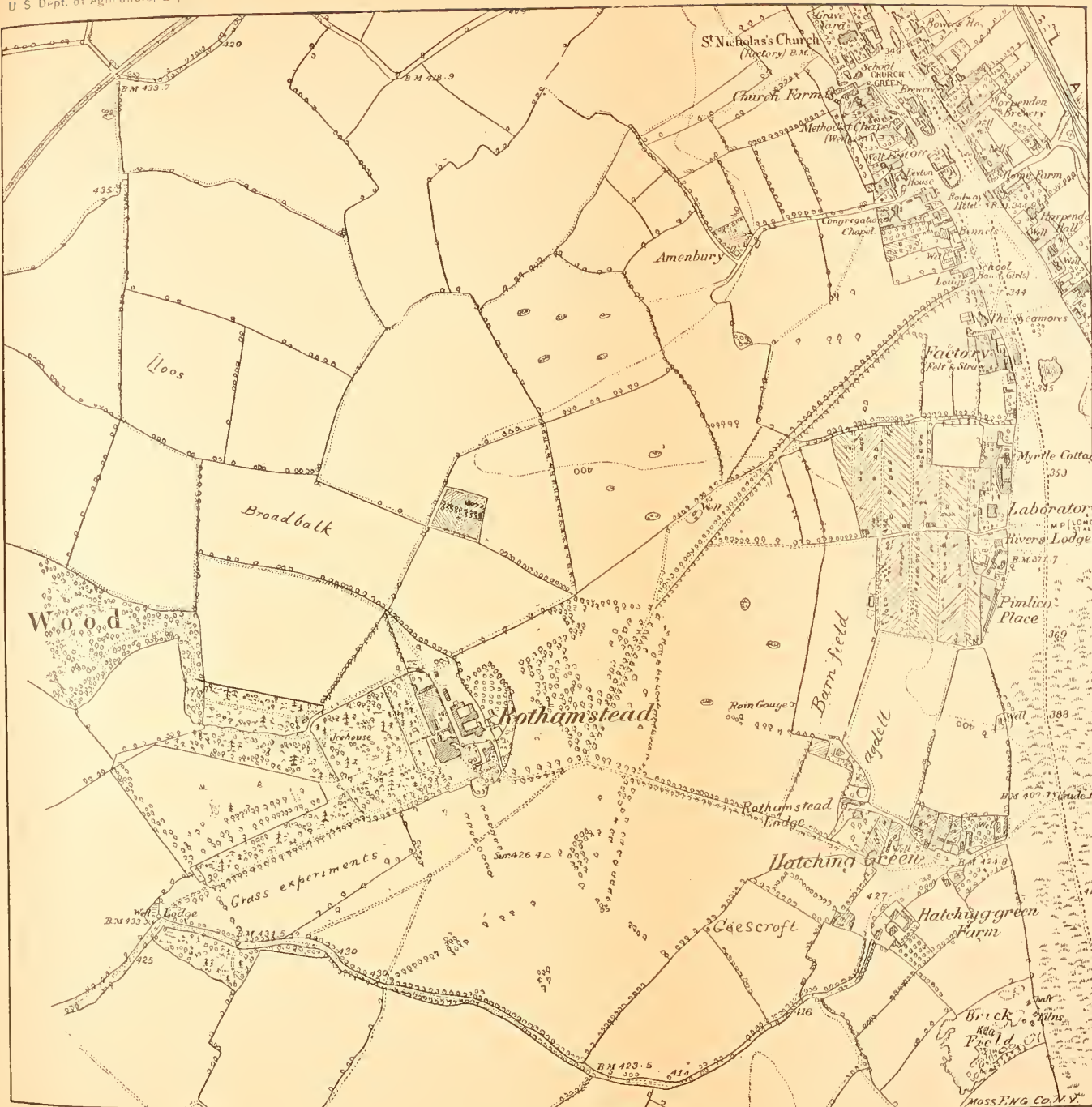
Crops.	When begun.	Duration.	Continued or ceased.	Plots.	Area.
		<i>Years.</i>			<i>Acres.</i>
Wheat.....	1844	48	Continued	37	11
Wheat and fallow	1851	40	Do.....	2	1
Wheat (varieties)	1868	15	Ceased.....	20	4-8
Barley.....	1852	40	Continued	29	4½
Oats.....	1869	10	Ceased.....	6	¾
Beans.....	1847	32	Do.....	10	1½
Beans.....	1852	27	Do.....	5	1
Beans and wheat.....	1851	28	Do.....	10	1
Clover.....	1849	29	Do.....	18	3
Leguminous plants*	1878	14	Continued	18	3
Turnips†.....	1843	28	Ceased.....	40	8
Sugar beet†.....	1871	5	Do.....	41	8
Mangel-wurzel†.....	1876	16	Continued	41	8
Potatoes.....	1876	16	Do.....	10	2
Rotation.....	1848	44	Do.....	12	3
Meadow.....	1856	36	Do.....	22	7

* Continuous with the clover.

† Continuous root experiments.

U. S.





MAP OF ROTHAMSTED.

The Rothamsted field experiments are unique. At no other station for agricultural investigations have trials in the field been carried out in the same systematic way or on such a large scale; the field experiments which approach them nearest are copies of those at Rothamsted. The mode of conducting these field experiments thus deserves our consideration.

In the earlier trials made upon turnips and wheat the manures varied a good deal from year to year and the same plot was not always treated in the same way; a more regular proceeding was, however, soon adopted, and has since been generally adhered to. In the later systematic experiments each plot receives every year the same manuring, unless a change of treatment is needed to attain some special object; one or more plots in each series are without manure; one usually receives each year a liberal dressing of farmyard manure; the other plots receive the various constituents of manure, either alone or in mixture. The substances applied are ammonium salts, sodium nitrate, superphosphate made from bone ash, potassium sulphate, magnesium sulphate, and sodium sulphate. The various constituents of plant food are thus applied in a soluble and active form, so that they may produce their maximum effect. The weight of each constituent applied is also known, so that the results admit of quantitative treatment.

The experiments with the various constituents of manure are arranged with the view to bringing into prominence the special characters of the nutrition of the crop under investigation. Thus, upon the unmanured plot and upon that manured with ammonium salts only, the crop is limited in its supply of ash constituents to the amount which it can obtain from the soil. Where the ammonia is supplied with superphosphate, the power of the crop to obtain alkalis from the soil is shown. Where ammonia and alkalis are employed the capacity for assimilating the phosphates of the soil is manifested. Where an ample supply of ash constituents without nitrogen is furnished the capacity of the crop for assimilating nitrogen from natural sources is made evident. Both the scientific and practical value of field experiments arranged on this system are very great. By such experiments we have learned the great dependence of our cereal crops upon the supply of nitrates within the soil; the greater influence of artificial supplies of phosphates upon barley than upon wheat; the greater influence of alkali manures upon wheat than barley; the extraordinary effect of phosphates upon turnips, and the comparative indifference of mangels to this manure; the want of effect of ammonia and nitrates upon leguminous crops; and the beneficial influence of potash. Facts of this description may not appear from trials in a single season, or even by experiments during several years if the soil at starting has been too rich in plant food, but if such a system of experiment is continued the characteristics of the nutrition of the crop will in time become manifest, the soil of the test plots becoming sufficiently impoverished to show by contrast the effect of manure.

It is an ordinary criticism upon field experiments to say that the results are true only for the particular soil in question, and can not safely be applied beyond the limits of the locality in which they were ascertained. This is true if the object of the experiment has been to ascertain the money value of any particular manure, but it is not true if the experiments have been arranged so as to throw light upon the characteristic peculiarities of the nutrition of a crop. The crop is the same and preserves the same characters wherever it is grown, while the quantitative effect of a manure depends primarily upon the richness of the soil to which it is applied.

The patient repetition of the same manurial conditions year after year upon the same land is a mode of experiment which has many advantages. By this means trustworthy averages are obtained of the amount of produce yielded under each condition of manuring, and ample information is afforded respecting the influences of seasons and the permanent or temporary value of the manures employed.

As a result of the same treatment long continued, the soil of the experimental field becomes altered, so that the different plots present very different conditions of food supply. On certain plots the crop now grows in soil specially exhausted of nitrogen, or phosphates, or alkalis, while in the soil of other plots an abundance of these constituents has accumulated. We thus obtain in the same field soils presenting far more extreme conditions of food supply than will ever occur in ordinary agriculture. Opportunity is now afforded not only for studying the capacity of the crop for obtaining plant food, but also of seeing the influence of extreme conditions of food supply upon the chemical composition of the vegetable produce.

Having established such conditions we are now in a position to attack questions relating to the chemistry of the soil, to ascertain to what extent the soil has been exhausted under certain conditions of treatment, to what extent accumulations of manure have taken place, and to what depth they have penetrated. In one of the fields at Rothamsted it has been possible by means of a system of drainpipes, to study the nature of the soluble matters removed from the manured plots in the drainage water.

Results of an entirely different class and of great interest to the botanist have been obtained by the continued application of different manures to the mixed herbage of permanent meadow land. It is difficult now to believe that the herbage was ever alike over the various plots in the grass experiment, and that the striking differences in the development of individual species of grasses, clovers, and weeds are simply due to the persistent application of certain chemical salts. The differences in the character of the herbage had become so marked in the second year of the experiment that a botanical analysis of the hay of the experimental plots was commenced in 1857, and has since then been systematically carried out.

Such are some of the advantages obtained by patiently continuing the growth of the same crop year after year upon the same land under fixed conditions of manuring.

THE WHEAT CROP IN BROADBALK FIELD.

It is beside the scope of this introductory lecture to describe any of the results of the field experiments, but as I shall have no other opportunity in these lectures for doing so, I will say a word or two now about the field which of all others has most interest for Americans; I refer to the Broadbalk wheat field. On taking an American agriculturist into this field a few summers ago he stopped and said, "Americans have learned more from this field than from any other agricultural experiment in the world."

You are aware that wheat has been grown in Broadbalk field every year for forty-eight years. There is certainly at present no appearance of any decline in its fertility. Last year nine of the manured plots gave a produce of dressed grain exceeding 40 bushels per acre and in one case it reached 50 bushels. The plot of greatest interest to you, however, is the one which has received no manure for fifty-two years; the average annual produce of this plot has been about $13\frac{3}{4}$ bushels of grain per acre, a quantity distinctly exceeding the average produce of the wheat-producing countries of the world. According to Sir John Lawes, the average produce of Australia, Canada, India, the United States, and ten European countries, comprising altogether an acreage of over 135,000,000 acres, is about 12.25 bushels per acre. The soil of the unmanured plot I need hardly say is in a very poor condition, containing in the first 9 inches not more than 0.10 per cent of nitrogen. The fact that wheat can be continuously grown on such a soil with fair results is due to the small demands of the crop and to its great capacity for appropriating the mineral food of the soil. In the four-course rotation at Rothamsted, which has been unmanured for forty-four years and all the produce removed, wheat has been the crop which has given the largest weight of produce per acre. It is to this characteristic of wheat that its successful use as a food crop for the human race is largely due.

Another experiment, however, made in Broadbalk reminds us that wheat is an exotic and that it is unable to hold its own in competition with native weeds. At the upper end of Broadbalk there is a margin of arable land which does not receive the experimental manures, but which up to 1882 has always been sown with wheat. After the summer of 1882 the crop on this portion was left standing, Sir John Lawes being curious to see what would be the result of self-seeding without the intervention of man. The first self-sown crop came up strong, but was so starved by the weeds that the produce of grain probably did not exceed a few pints per acre. The last appearance of the self-sown wheat was apparently in 1885; some wheat which appeared later was probably sown by birds. Before its entire disappearance the surviving plants

presented a singularly dwarfed aspect. The photograph shows the first produce of self-sown wheat contrasted with the ears produced in the same season by ordinary sowing; also a turf bearing wheat stalks producing only a single grain, which represents the last appearance of the plant. (Plate IV, Figs. 2 and 3.)

The practical difficulty attending the continuous growth of wheat is that of keeping the land clean, and this difficulty is of course greatest upon a heavy soil, in a moist climate, and with a poor wheat crop. At Rothamsted the growth of weeds in Broadbalk field is a subject continually causing much anxiety, although great pains are taken to clean the plots by hand labor.

Before leaving the subject of Broadbalk I will show you one more photograph, representing the wheat harvested in 1878 from seven of the plots. Plot 2 has received farmyard manure every year since 1844; plot 3 has been unmanured for the same period; plot 5 has received ash constituents only since 1852; plot 6, the ash constituents, with 200 pounds of ammonium salts; plot 7, the same, with 400 pounds of ammonium salts; plot 8, the same, with 600 pounds ammonium salts; plot 9, the ash constituents, with 550 pounds of sodium nitrate. The picture before you illustrates in a striking manner the preponderating effect of nitrogenous manures in determining the luxuriance of wheat. (Plate IV, Fig. 1.)

MODE OF CONDUCTING FIELD EXPERIMENTS.

There are some points in the arrangement and conduct of field experiments which are more or less essential to their accuracy and success, to which I should like to call your attention. All the plans I shall recommend have not been pursued at Rothamsted, but I think I am right in saying that when this is the case the fact has been a subject for regret.

I need hardly say that it is generally a mistake to select a rich soil as the subject for field experiments; when such a soil is operated on the effect of manures is at first very small, and much time and labor is wasted before the condition of the plots becomes sufficiently different to affect the crops in any decisive manner.

Another important condition is that the soil of the field should originally be of uniform character. The best way of commencing a field experiment is undoubtedly to mark out the plots, and in the first instance to grow the crop it is intended to study over the whole field without any application of manure, weighing the produce of every plot. By proceeding thus for one or more years any irregularities in the soil will be detected. For the same reason and also to furnish a basis from which future changes may be measured, it is important that the soil of each plot should be sampled and analyzed before the actual experiment commences. The Rothamsted method of soil sampling we shall describe in the next lecture.

The size and shape of the plots are also matters of considerable importance. Very small plots are always to be avoided, as the natural irregularities of an agricultural experiment may then easily equal or



Fig. 1.

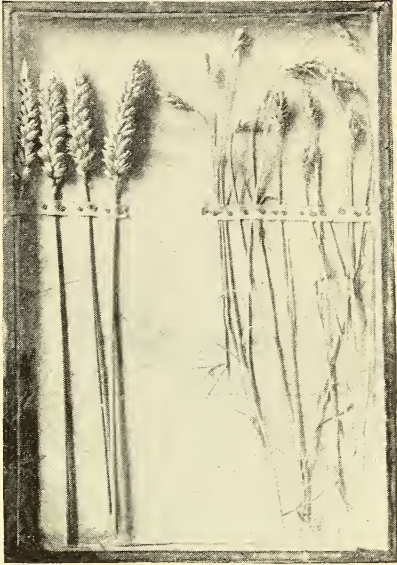


Fig. 2.



Fig. 3.

WHEAT GROWN AT ROTHAMSTED.

exceed the influence of the conditions it is desired to study. Small plots also generally mean that a considerable area of the field is occupied by footpaths, a condition fatal to truthful results, the supply of light, moisture, and plant food by the side of a footpath being much in excess of that in the midst of a crop. The earlier of the experimental fields at Rothamsted were not arranged as skilfully as the later ones; thus Broadbalk wheat field has long, narrow plots, and the influence of the manure of neighboring plots is in some cases distinctly felt. The barley experiments in Hoos field are the best laid out; here the plots are nearly square; they have each an area of one fifth of an acre.

The successful distribution of the artificial manures is a difficult matter. At Rothamsted this is done entirely by broadcast hand sowing, except in the rotation field, where the superphosphate is drilled with the turnips. A day free from wind is chosen; the artificial manures have been mixed with burned soil to increase their bulk; they are then distributed by hand, the broadcast sowers going twice over the ground in contrary directions. While the sowing is taking place canvas screens are carried by men along the boundaries of the plot, a little in advance of the sowers, to prevent any of the manure falling on the next plot. The sowing by hand is not regarded as perfectly satisfactory, but no machine at present seems capable of equally distributing a given weight of manure over a given area of land.

The manures used for the field experiments are prepared in a manure barn, which forms part of the farm buildings.

I must not now go into further details respecting the experimental crops, but pass to other departments of Rothamsted work.

INVESTIGATIONS RESPECTING PLANTS, RAIN, AND SOILS.

An investigation of the amount of water given off by plants during their growth was made in 1849-50. The plants examined included farm crops and young trees and shrubs, both evergreen and deciduous.

More important experiments were those relating to the assimilation of nitrogen by plants, commencing in 1857 and continuing till 1860. The plants, as you will probably recollect, were grown in ignited soil, under glass shades, so arranged that the plants could be supplied with washed air and water. No assimilation of nitrogen from the atmosphere took place in the case of any plant, including the beans, peas, and clover, grown under these conditions. You are aware that an American chemist, Dr. Evan Pugh, took a prominent part in this investigation. I was working in the Rothamsted laboratory during the whole of 1859, and shall never forget his great capacity for work and the energy and confidence with which every problem was attacked. I am glad to be able to show you a portrait of Dr. Pugh, taken in 1859, before he returned to America.

Quite recently (1888-91) the subject of the assimilation of nitrogen by leguminous plants has again been made the subject of experiment

at Rothamsted, and it has been found that assimilation of atmospheric nitrogen does in fact occur when the conditions of growth are those employed by Hellriegel and Wilfarth, that is when a little ordinary soil is added to the sand in which the plants are grown and the characteristic tubercles make their appearance upon the roots. This assimilation of nitrogen through the intervention of a microörganism which attaches itself to the root, is one of the most interesting discoveries of the present day. We now see why assimilation of nitrogen was not obtained in the earlier experiments; the cultivation in an ignited soil excluded the organism which under natural conditions performs this work.

The examination of rain water, with the view to determining the amount of combined nitrogen that is contributed by it to the soil, commenced in 1853, when the large rain gauge, having an area of $\frac{1}{1000}$ of an acre, came into use. This work has again recently been taken up, and the ammonia, nitric acid, chlorides, and sulphates in the rain water have been determined by improved methods.

Much work has been done of late years in analyzing the soils and subsoils of the experimental fields; the work at present is confined to determinations of total nitrogen, and in a more limited number of instances to determinations of carbon, nitric acid, and chlorine. Some of these results I hope to lay before you in subsequent lectures. No mineral analyses of the soils have yet been made in the Rothamsted laboratory.

EXPERIMENTS WITH ANIMALS.

The first feeding experiments with oxen and pigs commenced in 1847, and experiments with sheep in 1848. Subsequently experiments were made on a large scale upon the comparative fattening qualities of different breeds of sheep. Those upon Hampshire and Sussex Downs were made in 1850; those on Cotswolds in 1851; those on Leicesters and Crossbreds in 1852. A series of feeding experiments with pigs was made in 1850. Two series of experiments with oxen belonging to the Duke of Bedford were made at Woburn in 1849 and 1851. All these feeding experiments were conducted with analyzed foods, supplied in known quantities. The rates of increase obtained with various diets were thus ascertained. In many cases the quantity of manure produced was at the same time determined, but only certain general conclusions respecting this portion of the work have as yet been published.

A laborious series of experiments has been carried out to determine the composition of the bodies of oxen, sheep, and pigs. The weights and proportions of the separated parts and organs were determined in the case of a large number of animals (three hundred and twenty-seven), and in the case of ten selected animals a general chemical analysis was made, the proportion of water, fat, nitrogenous matter, and ash in the various parts being determined, and subsequently a complete analysis of the ash made. The greater part of this work was published in 1859,

the ash analyses in 1883. This line of investigation was for a long time peculiar to Rothamsted and but little work of the same kind has at present been attempted elsewhere.

The composition of the fattened animals, and especially of their increase while fattening, ascertained in these experiments, taken in connection with the composition of the food supplied, enabled Messrs. Lawes and Gilbert to maintain the doctrine of the formation of fat from carbohydrates at a time when it found little acceptance among physiologists.

The ash analyses of the whole bodies of animals are unique. They furnish information as to the loss of ash constituents which a farm suffers by the sale of stock.

The other investigations relating to animals have been upon the utilization of sewage, carried out in 1863-65; a comparison of the feeding qualities of malt and barley, in 1863-64; and experiments on the changes which take place during ensiling and on the fattening and milk-producing value of the product, in 1884-85.

Something should now be said about the laboratory and the work which is done there.

THE ROTHAMSTED LABORATORY.

It will be readily understood that with so many investigations in progress the work soon outgrew the capacity of the barn which served in the first instance for a laboratory. When, therefore, a number of agriculturists desired to present Mr. Lawes with a testimonial, and wished to know what form it should take, he replied, "Give me a laboratory." The construction of the laboratory commenced in 1854. It was opened at a public gathering, at which the Earl of Chichester presided, on July 19, 1855. The laboratory is built on the Rothamsted estate. It adjoins Harpenden Common, which forms a wide expanse of open ground in front. (Plate V.)

The principal analytical and botanical work is conducted in a large front room, about 39 by 25 feet, of the whole height of the building, lighted by a skylight in the roof and by windows along the front. There are various small rooms at both ends of this front laboratory appropriated to special purposes. In a small room facing north the gas analysis is conducted, and here my own bacteriological work was carried on. Behind the front laboratory lies the back laboratory. It is of the same dimensions as the front laboratory and contains the ash muffles and the large water oven. It is paved with brick, and is employed for the preparation of samples and for other rough work.

Around the upper part of the front laboratory there runs a gallery reached by a staircase. This gallery is fitted throughout with shelves occupied by bottles which contain samples of the experimental produce and of the ashes prepared from them. On the same level as this

gallery and projecting over the back laboratory is a drying room furnished with a stove and fitted with open iron shelves. Here the partial drying of soils, of sliced roots, and of other fresh produce was carried on till quite recently, the object being to bring these into a condition suitable for grinding or for storing till the sample for analysis could be prepared.

The number of samples of soils and of experimental produce had become so great that an additional building was constructed by Sir John Lawes in 1888. The new building consists of two lofty rooms lighted from the roof. The sides of one room are fitted with iron shelves, on which the sample bottles are stored. The other room contains a large press for parcels, and connected with it is the new drying room. There are at present in the laboratory about 5,000 bottles containing samples of soils, 5,000 containing grain from the experimental fields, 6,000 containing prepared samples of crops and foods, and more than 24,000 containing the ashes of crops and animals. The total number of sample bottles is about 41,000.

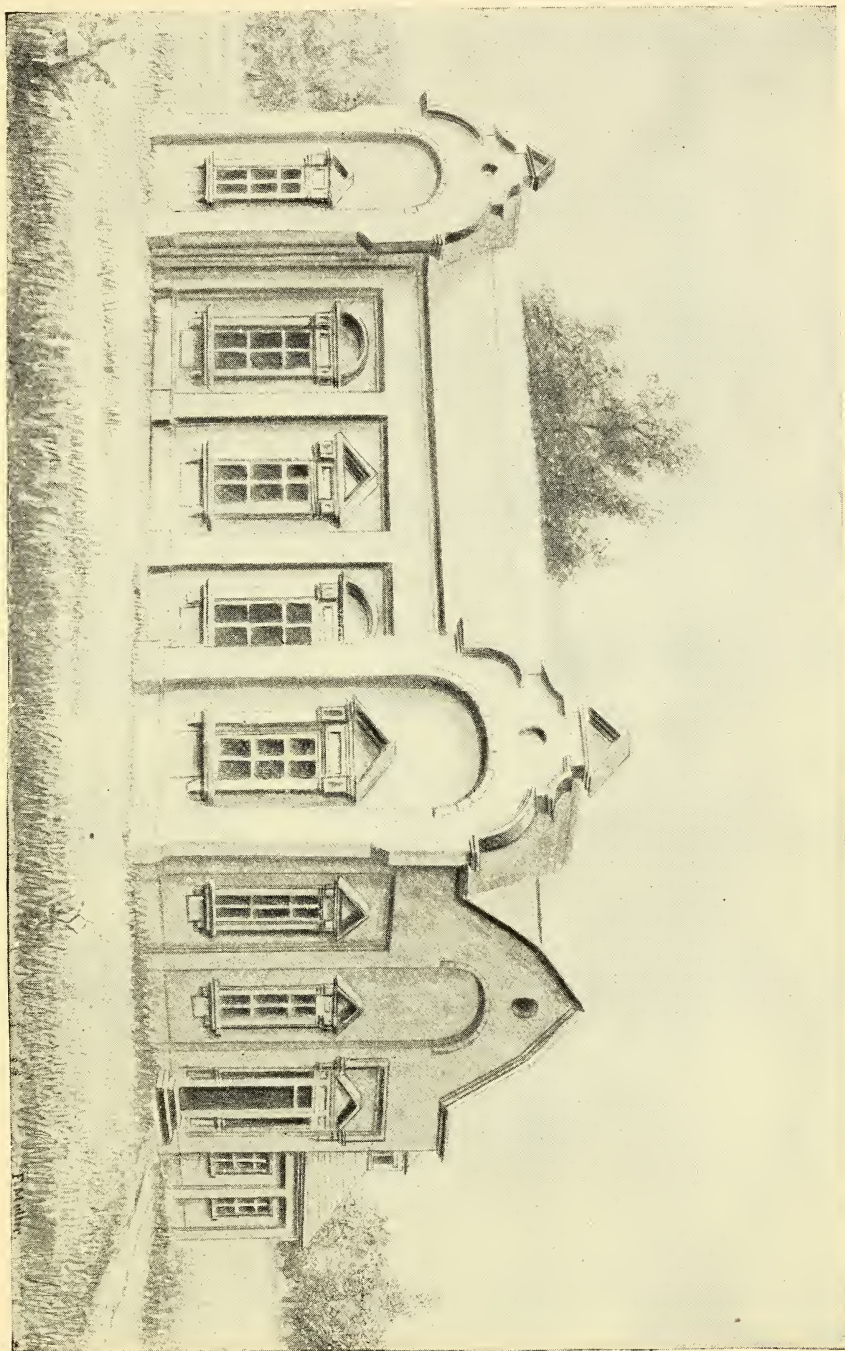
LABORATORY WORK.

A large portion of the laboratory work is of a routine character, and consists in the preparation of samples of the experimental produce and the determination of dry matter and total ash.

The dry matter is determined in the water oven on quantities of 20 ounces of grain or 12.5 ounces of straw or hay, or on partially dried potatoes equivalent to 50 ounces of the fresh tuber. The quantity of roots which is taken varies. Ten to thirty (or more) roots are taken, according to their size. They are divided into quarters by division through the long axis of the root, and each quarter treated as an independent sample. Before drying in the water oven, grain is crushed in a mill; hay and straw cut small by a chaff cutter; roots and potatoes sliced, strung on twine, and partially dried in the stove room. The materials to be dried are finally placed in numbered tin boxes and remain three days in the water oven; the boxes are then closed, allowed to cool, and weighed.

The dried material is used afterwards for the determination of ash. For this purpose it is placed on platinum trays and heated till ignition commences. The vegetable matter is at first allowed to smolder under a flue, inflammation being avoided. When natural combustion has ceased the platinum tray is placed in an iron muffle, through which a slow current of air passes, and brought to a low red heat, the temperature being slowly raised as the operation proceeds. The art of preparing ashes consists in carrying out the operation at as low a temperature as possible, as any fusion of the ash effectually prevents the combustion of the carbon. The determinations both of dry matter and ash are made in duplicate.

Next to the determination of dry matter and ash, the determination of total nitrogen forms the largest part of the routine chemical work.



ROTHAMSTED LABORATORY.

Nitrogen is generally determined (by the soda-lime method) in the roots, potatoes, and hay from the experimental fields, but it is only occasionally determined in the case of cereal produce. A large number of nitrogen determinations have been made in soil.

Besides the standard determinations of dry matter, ash, and nitrogen, there have been from time to time various detailed investigations made on the produce of the experimental fields, as for instance the detailed examination made of the various products obtained on grinding wheat; the determination of the losses which occur during the malting of barley and the preparation of silage; the detailed analysis of hay, turnips, sugar beet, mangels, and potatoes grown with different manures.

More than seven hundred analyses have been made by Mr. R. Richter, of the ashes from a selected series of the experimental crops. This is probably the finest series of ash analyses yet executed, and the most instructive, the results exhibiting the influence upon the composition of the ash of wide differences both in the supply of mineral food and in the character of the season. It is greatly to be regretted that most of these analyses are still unpublished.

The chemical analysis of the rain water, and of the drainage waters from the drain gauges and from Broadbalk wheat field were for many years under my own care. Of my own investigations upon nitrification, made in the Rothamsted laboratory, I shall have an opportunity of speaking in some of the subsequent lectures.*

I need hardly say that the calculation and tabulation of the results of the experiments is in itself no trifling work. An effort is made to keep duplicate copies of such tables in different places, so as to avoid the risk of loss by fire.

The staff at the laboratory under Dr. J. H. Gilbert usually consists of ten persons. Of these, three (of whom Mr. G. Dunkley is the chief) are in the calculation room and execute the clerical work of the establishment. Five are in the front laboratory; these include a chemist, Dr. N. H. J. Miller; an assistant (trained by Dr. Pugh), occupied in making

* My connection with Rothamsted has been briefly as follows: I spent the year 1859 in the laboratory, being occupied with the analysis of the ash of hay and wheat grain. During the next seven years I had no formal connection with Sir John Lawes; the greater part of the time was spent at the Royal Agricultural College at Cirencester, where I was the teaching chemical assistant. Here, however, I lectured upon the Rothamsted experiments and made analyses of some of the animal ashes. In 1867 I became chemist to Sir John Lawes's manure and tartaric and citric acid factories. In 1876, at his invitation, I came to Harpenden to take up investigation on the subject of soil in the Rothamsted laboratory. The work which has chiefly occupied me since that date consisted in the examination and improvement of analytical methods; the systematic analysis of rain, drainage, and well waters; the determination of nitrates, chlorides, and carbon in soils; a prolonged investigation of the process of nitrification; and a study of the chemical action of various microorganisms. The published results occupy about thirty papers. My connection with Rothamsted has now been terminated by the new managing committee.

nitrogen combustions; Mr. J. J. Willis, who supervises the preparation of samples, the botanical separations, and the field work; an assistant who makes the determinations of dry matter and prepares the samples of rain and drainage waters; and a boy attendant. In the back laboratory there are two, a general attendant, who prepares all the samples of ash, and a lad occupied in grinding and sampling.

METEOROLOGICAL WORK.

The rainfall has been determined, both by the large and by small ordinary rain gauges, since 1853. Records of temperature and pressure have been kept since 1873 by Mr. T. Wilson, to whom the instruments belong; they are now observed and the records made by the laboratory staff. Since the summer of 1890 a sunshine recorder has been added.

Rothamsted lies about 400 feet above the sea level. The climate is somewhat cooler and the seasons rather later than is general in this part of England; the rainfall is distinctly above the average of the eastern district.

PUBLICATIONS.

I need say but little on the subject of the numerous publications which have proceeded from Rothamsted, most of which are already in your hands. A series of volumes containing the collected papers of Messrs. Lawes and Gilbert has been lately sent to many American institutions. The annual memorandum sheet is also widely distributed. This remarkable publication was first issued in 1855, as a four-page sheet, for the convenience of the visitors attending the opening of the laboratory. The next issue was in 1862, the year of our international exhibition, when many foreigners visited Rothamsted. The size was then doubled and the arrangement became nearly what it is at present. The sheet was not at first published annually, but supplements were from time to time issued. Annual publication commenced in 1872.

A large number of the investigations remain at the present time unpublished.

THE NEW FOUNDATION.

It is one of the saddest facts of human life that all good work must cease. But though the work of the individual comes to an end, the work of the institution may continue. Sir John Lawes has desired that the work he has carried out at Rothamsted should continue, and for that purpose he has converted a private into a public institution; he has endowed it and started it upon its future course in his own lifetime, so that the new managers may acquire somewhat of the old experience and be able to take up the threads of unfinished investigations.

The trust deed by which this change was effected was signed on February 14, 1889. By this deed the laboratory, the experimental fields,

and £100,000 are made over to trustees, and directions are given for the election by certain scientific societies of a managing committee, of which the owner of Rothamsted is to be one. The present trustees are Sir John Lubbock Bart., F.R.S.; Lord Walsingham, F.R.S.; and Dr. John Evans, treasurer of the Royal Society. The committee consists of nine members, Dr. John Evans, treasurer Royal Society (chairman); Dr. Hugo Müller, F. R. S. (treasurer); Prof. M. Foster secretary Royal Society, and W. T. Thiselton Dyer, F. R. S., nominated by the Royal Society; Prof. H. E. Armstrong, F. R. S., by the Chemical Society; William Carruthers, F. R. S. (late president of the Linnean Society), by the Linnean Society; Sir John H. Thorold, Bart., and Charles Whitehead, F. L. S., by the Royal Agricultural Society of England; also Sir J. B. Lawes, F. R. S. Mr. H. Rix is secretary to the committee.

Every one interested in agriculture or desiring the advancement of science will heartily wish the new managers success in the important task which they have undertaken.

LECTURE II.

THE CIRCUMSTANCES WHICH DETERMINE THE RISE AND FALL OF NITROGENOUS MATTER IN THE SOIL.

Nature of the nitrogenous matter in soils—Origin of the nitrogenous organic matter: (1) Subsoil nitrogen; (2) surface soil nitrogen—Gains of nitrogen in soil: (1) Gains in pasture; (2) gains in clover land; (3) gains in a four-course rotation; summary—Sources of the nitrogen in surface soils: (1) Nitrogen from subsoil; (2) ammonia and nitrates from the air; (3) free nitrogen from the air—Limits to the accumulation of nitrogen—Losses of nitrogen—Influence of crop residues—Causes which determine loss of nitrogen—Tendency to equilibrium in soils—Rothamsted method of sampling soil.

We will all admit that the fertility of a soil is determined in great measure by the amount and character of the nitrogenous matter which it contains. It is clearly important, therefore, that we should study the origin of this nitrogenous matter, and become acquainted with any circumstances which tend to its loss or diminution. Without a correct knowledge of the circumstances under which soils may acquire nitrogen or of the conditions under which they may lose it, we can neither explain their present character nor take rational steps to improve their fertility or maintain the favorable condition they have already reached. The causes which determine the gains and losses of nitrogen in the soil are at the present day being actively investigated, and the subject is one upon which the last word is as yet far from being spoken.

NATURE OF THE NITROGENOUS MATTER IN SOILS.

I need hardly remind such an audience as I am now addressing that the nitrogen of soils exists in three very different forms of combination, as (1) ammonia, (2) nitrates, (3) nitrogenous organic matter.

The ammonia is generally insignificant in amount. Although itself a proper food for plants, it is only seldom that it has any importance from this point of view, owing to its rapid conversion into nitric acid.

The quantity of nitrates present in the soil is usually far more considerable than that of ammonia, though it is very rarely that 5 per cent of the total nitrogen of the soil exists in this State. The nitrates of the soil I need hardly say are of great agricultural importance. I hope, however, to speak at length on this subject in other lectures.

The great bulk of the nitrogen contained in soil occurs in combination with carbon and the elements of water, forming the so-called humic

compounds or nitrogenous organic matter of the soil. This humic matter is a mixture of various bodies, the precise nature of which has been very imperfectly ascertained, owing to their general insolubility and the absence of well-marked chemical properties.

ORIGIN OF THE NITROGENOUS ORGANIC MATTER.

We will probably all agree that the nitrogenous organic matter of soils is a residue left by the incomplete oxidation and decay of the dead tissues of previously existing plants and animals, and that it has its primary origin in the capacity possessed by plants of assimilating various forms of inorganic nitrogen and constructing therefrom nitrogenous organic bodies containing nitrogen, carbon, hydrogen, and oxygen, with the addition in many cases of a small quantity of sulphur.

(1) *Subsoil nitrogen*.—This plant growth may have occurred in the ocean, and the mud deposited at the bottom of the ocean containing the residues of vegetable and animal life may have finally been raised to the position of dry land, the nitrogenous matter of which was thus derived from the remains of the dead vegetable and animal life of the deep sea.

There are probably very few sedimentary rocks which do not contain an appreciable amount of nitrogenous organic matter. A specimen of calcareous clay (Oxford clay) obtained in a boring from a depth of about 500 feet below the surface, when analyzed in the Rothamsted laboratory, was found to contain 0.04 per cent of nitrogen, an amount equal to that generally present in the clay subsoils at Rothamsted. This nitrogen was associated with organic carbon. The amount of nitrogenous matter contained in the sedimentary rocks of our globe is enormous and is mostly of very ancient origin.

At Rothamsted the sampling of the subsoil has been carried out in many cases to a depth of 9 feet from the surface. The clay subsoil varies a great deal in different places. It may contain as much as 0.06 per cent of nitrogen or as little as 0.03, but there is, on the whole, little indication that the nitrogen is a diminishing quantity as we descend, after a certain distance from the surface has been reached. The nitrogen of this deep subsoil is, I think, to be regarded as in great part of ancient origin, belonging in fact to the clay when originally deposited. A sandy subsoil is usually poorer in nitrogen than one of clay.

(2) *Surface soil nitrogen*.—The nitrogenous matter of our surface soils, with which agriculture is chiefly concerned, is undoubtedly in greatest part of modern origin, and the processes which bring about its accumulation and diminution are at the present day in progress under our own eyes and deserve our most careful study.

No one can glance at a table of analyses of soil, taken from various depths at the same place, without seeing at once that nitrogenous matter has been produced or has accumulated at the surface. Illustrations of this fact, taken from analyses both of English and American soils, are

before you in Table II. In every case the surface soil is far richer in nitrogen than the subsoil below it. The figures given for arable Rothamsted soil are the mean of all the analyses made of Agdell field. The figures for old pasture are the mean of all the analyses made of the park soil, excluding only analyses of surface soil taken separately from subsoil. In all the subsoil analyses the results of samples containing chalk are excluded. The soils from Manitoba were analyzed in the Rothamsted laboratory.

TABLE II.—*Nitrogen in soils at various depths.*

(1) ROTHAMSTED SOILS.

Depth.	Arable soil.		Old pasture soil.	
	Per cent.	Pounds per acre.	Per cent.	Pounds per acre.
First 9 inches	0.120	3,015	0.245	5,351
Second 9 inches	0.068	1,629	0.082	2,313
Third 9 inches	0.059	1,461	0.053	1,580
Fourth 9 inches	0.051	1,228	0.046	1,412
Fifth 9 inches	0.045	1,090	0.042	1,301
Sixth 9 inches	0.044	1,131	0.039	1,186
Total 54 inches .....	.....	9,554	.....	13,143
Seventh 9 inches	0.042	1,049	.....	.....
Eighth 9 inches	0.041	1,095	.....	.....
Ninth 9 inches	0.044	1,173	.....	.....
Tenth 9 inches	0.043	1,076	.....	.....
Eleventh 9 inches	0.043	1,112	.....	.....
Twelfth 9 inches	0.045	1,198	.....	.....
Total 9 feet .....	.....	16,257	.....	.....

(2) MANITOBA SOILS.

Depth.	Brandon.	Niverville.	Winnipeg.	Selkirk.
	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>
First foot	0.187	0.261	0.428	0.618
Second foot	0.109	0.169	0.327	0.264
Third foot	0.072	0.069	0.158	0.076
Fourth foot	0.019	0.038	0.107	0.042

In the experimental wheat field at Rothamsted the amount of nitrogen was ascertained some years ago for each 3 inches of depth. The difference between the first and second 3 inches was not great, this part of the soil being regularly mixed by the plow; the third 3 inches showed a distinct diminution in nitrogen; the fourth 3 inches was, in the case of the permanently unmanured land, but little removed in composition from the deeper subsoil, but in the case of the heavily manured land the effect of the manure or crop residue was still distinctly shown, though only to a small extent. Below the depth of 1 foot even the large dressing of farmyard manure which had been applied annually for twenty-five years became scarcely perceptible. Under prolonged kitchen garden culture the subsoil becomes enriched with nitrogenous matter to a far more considerable depth; this has been shown by the

analyses of the soil of the old kitchen garden at Rothamsted. This is doubtless due to the practice of deep trenching employed by gardeners.

With undisturbed soils, lying in natural prairie or farm pasture, the difference between the proportion of nitrogen in the surface soil and in the subsoil is far greater than in the case of arable land, and the line dividing the surface soil and subsoil is generally sharply drawn.

The nitrogenous organic matter which we find accumulated at the surface of all fertile soils, and especially in the case of pastures which have not been disturbed by the plow, has clearly had its origin in the growth and decay of a modern terrestrial vegetation.

The character of the organic matter contained in a surface soil is distinctly different from that present in the subsoil which lies beneath it. This is plainly shown by the difference in the proportion of carbon. The first 9 inches of the old pasture soils at Rothamsted, with the roots as far as possible removed, contain nitrogen and carbon in the proportion of 1 to 13,* while in the clay subsoil of the same land below 3 feet from the surface the proportion of nitrogen to carbon is 1 to 6. In the wheat land at Rothamsted the usual proportion of nitrogen to carbon is 1 to 10 in the first 9 inches from the surface. The nitrogenous matter at the surface is thus much richer in carbon than that in the subsoil, and approaches more nearly in composition to ordinary vegetable matter.

GAINS OF NITROGEN IN SOIL.

(1) *Gains in pasture.*—We have already remarked that the accumulation of nitrogenous matter in a soil is a process which is in many cases proceeding at the present day under our own eyes. Good illustrations of the fact are afforded in the operation of converting arable land into pasture. At Rothamsted arable land has at various times been laid down in grass and converted into permanent pasture. This has been done in an ordinary agricultural manner, the land sown with grass receiving farmyard and other manures, or being pastured by cattle fed with cotton cake. In Table III will be found the percentages of nitrogen contained in the first 9 inches of the ordinary arable land of Rothamsted farm and in certain fields which have been in pasture for periods of various duration.

TABLE III.—*Examples of increase of nitrogen in Rothamsted soils laid down in pasture.*

	Age of pasture.	Nitrogen in first 9 inches.
	<i>Years.</i>	<i>Per cent.</i>
Arable land.....		0.140
Barn-field pasture.....	8	0.151
Apple tree pasture.....	18	0.174
Dr. Gilbert's meadow.....	21	0.204
Dr. Gilbert's meadow.....	30	0.241

* The Manitoba soils mentioned in the table contained in the first foot from 12.2 to 14.2 of carbon for 1 of nitrogen.

Approximate nitrogenous statistics of Dr. Gilbert's meadow, twenty-three years, 1866-'88.

	Nitrogen per acre.			Nitrogen per acre.
	At 0.64 per cent in dung.	At 0.80 per cent in dung.		
In surface soil, 1866	<i>Pounds.</i> 3,497	<i>Pounds.</i> 3,497	In surface soil, 1888.....	<i>Pounds.</i> 4,690
In manure, 1866-'88	1,520	1,801	In hay, 1866-'88.....	1,339
From air or subsoil	5,017	5,298	Total	6,029
Total	1,012	731		
Gain per annum	6,029	6,029		
	44	32		

It will be noticed that within the comparatively short number of years attained by these pastures the nitrogen in the surface soil has risen with each increase in the age of the pasture. In the case of Dr. Gilbert's meadow the increase of nitrogen in the surface soil during thirty years has been at the rate of about 50 pounds per acre per annum.

As all the soils we have just referred to have received manure while in pasture, it is of course conceivable that the increase of nitrogen in the soil is due to that added in the manure. In the case of Dr. Gilbert's meadow, however, a careful account has been kept during twenty-three years of the quantity of manure applied; the meadow has also been mown every year and the hay weighed. A sufficient number of facts are thus known to enable the nitrogen statistics of the field to be calculated approximately. The field has received farmyard manure (London dung) every alternate year, with small annual dressings of superphosphate, potassium sulphate, and sodium nitrate. Under this treatment the field has shown a steady increase in fertility, the hay crop averaging 1 ton, 8 cwt. during the first eight years (1866-73); 1 ton, 14 cwt. during the succeeding eight years; and 2 tons, 3 cwt. during the seven years from 1882-88. The exact amount of nitrogen contained in the dung is uncertain; two estimates are therefore given in the table, the nitrogen being reckoned both at 0.64 and 0.80 per cent of the manure. It will be seen that on either assumption there has been a very considerable gain of nitrogen over and above the amount applied as manure. The gain must indeed have been greater than the 44 pounds, or 32 pounds per annum shown in the table, for the whole of the nitrogen of the manure has been charged to the field and no account taken of any losses of nitrogen occurring either in the soil or the crop.

(2) *Gains in clover land.*—The Rothamsted results afford also a good example of the increase of nitrogen in the surface soil when a red clover crop is grown. In Little Hoos field, after six successive crops of wheat, oats, and barley, grown with artificial manures, the land was in 1873 divided and one half of the field sown with ordinary red clover and the other half with barley, both unmanured. The clover was a good crop, yielding 54 cwt. of hay per acre, containing about 150 pounds of nitrogen.

After the clover crop was removed the soil was carefully sampled, both where clover and where barley had been grown. The clover soil yielded in the first 9 inches 0.1566 per cent of nitrogen and the barley soil 0.1416 per cent, showing a considerable increase of nitrogen in the surface soil where the clover had been grown. The increase of fertility resulting from the growth of clover was also very remarkable, for in the following year the unmanured barley on the clover land yielded 58 bushels, while the barley on the other half of the field (following barley) yielded only 32.75 bushels.

There are many other Rothamsted experiments showing the increased fertility which results from the growth of beans or red clover; a grain crop taken after beans or clover is indeed frequently equal and occasionally exceeds a similar crop grown in the same season after a bare fallow.

(3) *Gains in a four-course rotation.*—We have also evidence, I think, of gains of nitrogen occurring during a four-course rotation. I do not by any means wish to assert that at the end of a four-course rotation the soil is necessarily richer in nitrogen than at the beginning, unless indeed the land has been liberally manured with farmyard manure, but I would call attention to the fact that the amount of nitrogen removed in the crops of a four-course rotation is so considerable that if the fertility of the land is maintained we must conclude that a notable quantity of nitrogen has been supplied to the crops which was not originally present in the surface soil. In the Rothamsted rotation field the ordinary Norfolk four-course rotation of swedes, barley, clover (or beans), and wheat has been in operation for over forty years. On the plots which have been supplied with ash constituents or with ash constituents and nitrogen, the average annual amount of nitrogen removed in the crops in excess of that contained in the manure, has been over 30 pounds per acre. In the absence of facts I can not assert that the surface soil is not now poorer in nitrogen than at the commencement of the experiment; but the whole amount of nitrogen removed in the crops is too great to be thus explained; neither has the fertility of the land diminished in such a way as to make such an explanation probable. We have here, then, fresh evidence of the utilization, though not of the accumulation, of very considerable amounts of nitrogen, obtained beyond the limits of the surface soil. The details of the experiments show that the acquisition of nitrogen is to a large extent dependent on the presence of a leguminous crop in the rotation.

Summary.—The facts I have brought before you from the Rothamsted investigations agree, I think, with the general results of agricultural experience—they point to a considerable and long-continued gain of nitrogen in the surface soil when arable land is laid down under favorable conditions in permanent pasture; and to a gain of nitrogen in the soil, or to its utilization by crops from sources beyond the surface soil, when leguminous plants are cultivated, either alone or as members of a rotation.

It must not be supposed that a leguminous crop necessarily leaves a soil richer in nitrogen than it was before its growth. The sensible increase in the soil takes place only when the soil at starting was not too rich in nitrogenous organic matter and when the leguminous growth was abundant. The composition of the soil where beans have been continuously grown at Rothamsted exhibits apparently no gain in nitrogen. The rich kitchen garden ground at Rothamsted shows a considerable loss of nitrogen during the continuous growth of red clover. But in all these cases the fact of the gain of nitrogen can probably be established if we regard the large amount of nitrogen removed in the crop and take into consideration the serious losses of nitrogen which are always in progress in soil and especially in a rich soil.

SOURCES OF THE NITROGEN IN SURFACE SOILS.

To proceed with our argument, we must now inquire: What are the sources of the nitrogen which we find accumulated in the surface soil? That the nitrogenous organic matter in soil is a residue of that previously existing in the plant, has been already acknowledged; we have then to ask: From what source did the plant obtain its nitrogen? There are three principal answers given to this question. These answers are not necessarily antagonistic; each may be a part of the truth, but at the present day each view finds its own special adherents.

(1) *Nitrogen appropriated from the subsoil.*—The first answer we have to notice affirms that a notable part of the surface nitrogen is merely the nitrogen of the subsoil which has been collected by the roots of plants and redeposited in the surface soil on their death. That such a transference from the subsoil to the surface actually takes place, it would be impossible to deny; but it is also quite clear that if the subsoil is to be an efficient source of surface nitrogen, its impoverishment by the growth of a crop must exceed its enrichment from the surface by crop residues and drainage, its losses must in fact be greater than its gains. Of this at present there seems to be no actual proof.

It is very unfortunate that the clay subsoils at Rothamsted vary so much in composition, even within short distances, that it is impossible to argue with certainty from the difference in composition shown by the subsoils of different plots and fields. The very numerous determinations of nitrogen in subsoils which have been made at Rothamsted do not therefore at present furnish any conclusive answer to the question before us. The supposition that the surface soil derives considerable supplies of nitrogen from the subsoil is thus at present little more than a possibility, to which no definite value can be attached.

(2) *Ammonia and nitrates appropriated from the air.*—The next answer we have to consider regards the combined nitrogen of the atmosphere, its ammonia, and nitric acid as the only original source of the nitrogen of vegetation, and therefore of the nitrogen in soils. Until recently this was the view generally entertained both by chemists and

physiologists. That the ammonia and nitric acid of the air are among the sources of soil nitrogen, will probably be denied by no one; the question now is, rather, are they the only sources? Are they sufficient to account for the accumulations of nitrogen which take place in our surface soils?

The amount of ammonia and nitric acid brought to the soil by rain and by the other aqueous deposits collected on the rain gauge, has been determined in many places. If the rain is collected far from large towns, the quantity of combined nitrogen which it contains is very small. In Table IV you will find the quantities of combined nitrogen found in the annual rainfall at Rothamsted, at Lincoln, New Zealand, and in Barbadoes. The total quantity of nitrogen has in these cases amounted to only 3.37, 1.74, and 3.77 pounds per acre, amounts which we see at once are quite incapable of accounting for the very considerable annual gains of nitrogen which have been ascertained in many instances to take place in the surface soil.

TABLE IV.—*Nitrogen as ammonia and nitric acid in rain, pounds per acre per annum.*

Nitrogen as—	Rothamsted, England, 8 years.	Lincoln, New Zealand, 3 years.	Barbadoes, 3 years.
Ammonia	2.53	0.74	0.93
Nitric acid	0.84*	1.00	2.84
Total.....	3.37	1.74	3.77

* Average of three years.

It is evident that if the ammonia and nitric acid of the air are to be of any considerable agricultural importance they must be taken up directly by crop or soil to an extent far beyond that which takes place through the medium of rain. The amount of ammonia and nitric acid in the air is certainly extremely small, but the air that is in contact with crop and soil is being constantly renewed. It is therefore by no means impossible that the quantities absorbed may become considerable.

Of the assimilation of gaseous ammonium carbonate by the leaves of plants we have at present but little knowledge, and we must be content to pass over this part of the subject. Of the absorption of atmospheric ammonia and nitrates by moist surfaces and by soil we have more information. I will refer only to Schlösing's numerous experiments with soils, published last year (*Compt. rend.*, 110 (1890), 429, 499). He found that moist soils freely exposed to the air took up nitrogen at the rate of about 38 pounds* per acre per annum and sub-soils somewhat less. Proof is given that ammonia was the principal

* This is the mean of six experiments, the results being corrected so as to represent a normal exposure to air. The actual absorption in the current of air used by Schlösing was considerably larger.

substance absorbed. In the moist soils the gain appeared as nitrates. The experiments were apparently conducted in Paris; the figures obtained are therefore probably too high for the open country, but they certainly show that the absorption of combined nitrogen from the air by the soil may reach a figure which is of agricultural importance.*

We ought not, however, to conclude hastily that the whole of the combined nitrogen supplied by the atmosphere is a clear gain to the soil and crops; we must first inquire what is the source of the combined nitrogen which the air supplies. With regard to the nitrogenous organic matter contained in rain and dust, it is clear that this has come from a crop or soil, and can be at best only a local addition to terrestrial nitrogen, at the expense of a loss in some other place.

The same must be said of that portion of the ammonia which has been derived from exhalations from the land. Schlösing, however, teaches, and apparently with reason, that the chief source of atmospheric ammonia is the tropical ocean. The store of nitrogenous organic matter contained in the ocean is enormous. Into the sea the nitrates removed by drainage from the land are poured, with the sewage of civilized countries.† If the present system of land and water has been sufficiently long in existence to arrive at a condition of mutual balance, we should not expect the oceanic ammonia of the atmosphere to supply more to the land, on the whole, than was removed from the land by the discharge of rivers into the sea, plus a certain supplementary quantity to be presently mentioned. The main result of the supply of atmospheric ammonia to the soil would, on this supposition, be to maintain the present status of soil nitrogen by bringing back to the soil what it had lost, although of course local gains and losses might occur to a considerable extent.

In the case of the nitrates and nitrites present in the atmosphere, we stand on different ground. It is well known that the electric discharges in the atmosphere effect a combination of the nitrogen and oxygen, and for many years this was regarded as the only natural operation whereby the amount of combined nitrogen in the world was increased. We must not, however, conclude that the whole of the nitrates and nitrites in the air represents a new combination of nitrogen gas; a part is doubtless due to the oxidation of ammonia by ozone or hydrogen peroxide.

The nitrogen present in the air as nitrates and nitrites is far smaller in quantity than that present as ammonia; the oxidized nitrogen is, moreover, according to Müntz, confined to the lower stratum of the

* Occasionally the large rain gauge at Rothamsted remains filled with snow for several weeks. When this snow melts it yields a dirty water, containing three or four times as much ammonia and nitric acid as is found in the average rain. There has clearly been a considerable gain during the prolonged contact with the atmosphere, and the adjoining fields must have gained nitrogen to a similar extent.

† In England the annual loss to the soil by the removal of nitrates in subsoil water is probably on an average about 7 or 8 pounds of nitrogen per acre, but the whole of this does not reach the sea.

atmosphere, while the ammonia is found at great heights. It is important also to notice that the production of nitrates in the atmosphere is far more considerable in the tropics than in temperate regions. The rain water of the tropics is thus characteristically rich in nitrates; this has been already shown by Müntz, and is illustrated by the analyses of Barbadoes rain given in Table IV.

The atmospheric nitrates brought by rain into the ocean are clearly, so far as they are derived from nitrogen, capable of supplying ammonia which shall be a clear gain to the land, and capable of doing something toward a general accumulation of nitrogen in the surface soil; but it may well be doubted if the whole supply of nitrogen as nitrates from the atmosphere exceeds or even equals the loss of nitrogen due to the reduction of nitrates in soils and waters.

On the whole perhaps the best conclusion we can come to, from the small amount of evidence at our disposal, is that the present supply of atmospheric combined nitrogen may be sufficient for a moderate yearly gain in soil nitrogen, when the conditions of the soil are such that the losses of nitrogen are reduced to a minimum—under such conditions, in fact, as obtain when land is laid down in pasture. On the other hand the atmospheric combined nitrogen appears quite insufficient to account for the large and rapid gains in nitrogen, amounting sometimes to 300 pounds per acre per annum, which frequently occur during the cultivation of leguminous crops.

(3) *Free nitrogen appropriated from the air.*—You are aware of the entire change of view which has taken place in recent years respecting the nutrition of leguminous plants. The proof has so multiplied that I think it is now admitted by all that the microbe which forms the tubercle upon the roots of leguminous plants does in some way, not at present understood, determine a fixation of the free nitrogen of the air and the formation from it of nitrogenous organic matter. A leguminous plant thus not only obtains ordinary supplies of nitrogen from the soil by means of its root hairs, but it also obtains an extraordinary supply of nitrogen from the air by means of the organisms forming its tubercles. The proportion between the two supplies is probably determined to a great extent by the richness of the soil in nitrogenous matter. We have thus at last an explanation of the very large gains in nitrogen generally obtained in leguminous crops, and of the considerable enrichment of the soil in nitrogenous matter by the crop residue which remains after the growth of such plants. These facts have been made the subject of Rothamsted investigations, but it is beyond the scope of the present lecture to refer to them in detail.

While, however, agricultural chemists are agreed as to the power of leguminous crops to determine the fixation of free nitrogen through their tubercles, they are by no means agreed as to whether or not this power can be exercised by a soil in which no leguminous plant is growing. It is freely admitted that the organisms, which when united with

the roots of a leguminous plant determine the fixation of nitrogen, are present in ordinary soils, but it is not yet established that when living in soil they assimilate free nitrogen. Berthelot, as you are aware, claims that most soils when in a moist but not wet condition, absorb nitrogen from the air, and his published experiments show generally very considerable gains in nitrogen in soils which have been exposed for a few months to air. Schlösing has repeated these experiments, using soils of many kinds, including some which had lately grown leguminous plants; in no case has he experienced a gain of nitrogen when the soil is placed in contact with a limited volume of air, but in a free current of air a considerable gain of nitrogen may occur, which Schlösing shows to be due to an absorption of ammonia. For the present we can not, I think, affirm that soils are enriched by the free nitrogen of the air, except through the medium of a leguminous crop; the whole subject is, however, ripe for investigation. We have in the tubercles of our leguminous crops an ample supply of "pure cultures" of the microbes whose properties we wish to study; we must attempt to grow them in appropriate artificial media, and ascertain under what circumstances a fixation of nitrogen occurs.*

LIMITS TO THE NATURAL ACCUMULATION OF NITROGEN.

It is a fact both of scientific interest and of great practical importance, that the enrichment of a soil with nitrogen is confined to certain limits, which can with great difficulty be exceeded. The limit varies according to the conditions in which the soil is placed. A familiar instance of this limit is afforded by a pasture. We have seen that when arable land is laid down in grass an accumulation of nitrogen takes place in the surface soil; this accumulation may be slow or rapid, according to the treatment of the field, but in the case of an ordinary dry meadow the accumulation does not pass a certain point. After a certain number of years no further rise in nitrogen appears in the soil, although the external conditions of the meadow remain precisely the same as they were when the former accumulation of nitrogen took place. The permanent pasture in Rothamsted Park has certainly been in grass for several centuries, but the soil is but little richer in nitrogen than that of Dr. Gilbert's meadow, which has been in grass for thirty-three years. The increase of nitrogen in the park soil has long ago ceased.

I need scarcely remind you also that there are narrow limits to the gains of nitrogen which may occur from the cultivation of leguminous crops. After a certain number of years the leguminous crop becomes feeble and dies, and the farmer is forced to adopt a change of culture.

A similar limit to accumulation is observed in the case of arable land receiving every year a liberal dressing of farmyard manure. If such

* Since this lecture was given, Schlösing, jr., and Laurent have shown that certain cryptogamic plants, not yet particularized, have apparently the power of assimilating the free nitrogen of the atmosphere (*Compt. rend.*, 113 (1891), 776).

a soil is analyzed from time to time it will be found that the annual accumulation of nitrogen in the soil due to the liberal manuring, steadily diminishes, till at last a point is reached at which the percentage of nitrogen in the soil no longer increases, notwithstanding the large amount supplied each year in the manure. The farmyard-manure plot in Broadbalk wheat field has received dung every year since 1843 at the rate of 14 tons per acre; this manure supplied annually about 200 pounds of nitrogen per acre. In 1865 and again in 1881 the soil was analyzed. The gain to the soil in nitrogen during the first twenty-one years averaged about 53 pounds of nitrogen per annum; in the second period of sixteen years the gain averaged about 11 pounds per annum. The rate of gain was of course much larger than 53 pounds at the commencement of the whole period and smaller than 11 pounds at the end of it. We have here a very striking lesson as to the wastefulness of large dressings of dung; but we can not dwell now on this aspect of the subject.

We do, however, sometimes meet with conditions in nature which admit of a practically unlimited accumulation of nitrogenous organic matter; such conditions occur to the most marked extent in a peat bog. The peat moss and the other plants inhabiting the bog are abundantly supplied with water, the drainage from land at a higher level; this water furnishes an unfailing supply of plant food. But the water discharges also another function: By keeping the bog in a saturated condition air is practically excluded from the soil, and the oxidation of organic matter is reduced to a minimum. Deep black soils, as those of Manitoba, have probably been formed under circumstances of this character. Under such conditions the dead vegetable matter annually produced is preserved and the peat continues to increase in thickness. Excess of water and a low temperature are prime factors for the large accumulation of nitrogenous humic matter.

We shall more easily understand the cause of the limit to the increase of soil nitrogen when we have considered the next part of our subject.

LOSSES OF NITROGEN IN SOIL.

In all the examples we have given of a considerable accumulation of nitrogen under the conditions of ordinary agriculture, the soil has always been under a crop and has generally been in a consolidated state. As soon as these conditions are reversed and the clover lay or the pasture land is turned over by the plow, a rapid loss of the accumulated nitrogenous matter sets in. As all our arable land was once pasture or woodland and now contains far less nitrogen than is found in pasture or woodland, the losses of nitrogen that have been brought about by arable culture are very apparent. Sir John Lawes in his paper on Fertility compares the soil of the old pasture at Rothamsted with that of Broadbalk field, which has certainly been for more than 250 years under arable culture, and concludes that about 3,000 pounds of nitrogen per acre have disappeared from the arable land since it came under the plow.

In Table V you will find examples of the decrease of nitrogen in Rothamsted soils under various extreme conditions of culture.

TABLE V.—*Examples of decrease of nitrogen in Rothamsted soils.*

	Nitrogen in first 9 inches.
	<i>Per cent.</i>
Old pasture.....	0.250
Arable land in ordinary culture.....	0.140
Wheat unmanured thirty-eight years.....	0.105
Wheat and fallow unmanured thirty-one years.....	0.096
Barley unmanured thirty years.....	0.063
Turnips unmanured twenty-five years.....	0.085

Where wheat or barley have been grown continuously without manure for many years the nitrogen of the soil falls to a point considerably below that reached in ordinary arable culture. The reduction has been still greater under continuous turnip culture, a result doubtless due in part to the greater oxidation which occurs from constant stirring of the soil during the summer. The figures in this table certainly give no support to the idea that arable soils not growing leguminous crops, are capable of obtaining large supplies of nitrogen from the atmosphere.

Broadbalk field, which has been cropped with wheat since 1844, supplies many illustrations both of the conditions under which the nitrogen of the soil may be diminished and of those under which it may be maintained or increased. Samples of the soil of many of the plots were very carefully taken in the autumn of 1865 and again in the autumn of 1881. The manuring of certain plots and their average produce in wheat during the sixteen years between the two dates of soil sampling are shown in Table VI, with the alteration in the nitrogen content of the first 9 inches of the soil during the same period, in pounds per acre.

TABLE VI.—*Manuring, produce of wheat, and alteration in the composition of the soil in Broadbalk field, Rothamsted, from 1865 to 1881.*

Plot.	Manures per acre annually applied 16 years, 1865-81.	Average produce per acre.		Nitrogen per acre in first 9 inches of soil.		
		Dressed grain.	Total produce.	1865.	1881.	Gain or loss in 16 years.
		<i>Bushels.</i>	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>
3.....	Unmanured.....	11 $\frac{1}{2}$	1,715	2,507	2,404	—103
5a....	Mixed mineral manure.....	12 $\frac{3}{4}$	1,963	2,574	2,328	—246
10a...	Ammonium salts 400 pounds.....	17 $\frac{1}{2}$	2,881	2,548	2,471	—77
11a...	Ammonium salts with superphosphate.....	23 $\frac{1}{4}$	3,856	2,693	2,676	—17
7a....	Ammonium salts with mixed mineral manure.....	28	4,993	2,829	2,908	+ 79
9a....	Nitrate of sodium 550 pounds and mixed mineral manure.....	36	6,949	2,834	2,883	+ 49
16a...	Unmanured*.....	13 $\frac{1}{2}$	2,194	2,907	2,557	—350
2.....	Farmyard manure 14 tons.....	31 $\frac{1}{2}$	5,356	4,329	4,502	+173

* During 1852-64 received annually ammonium salts 800 pounds, with mixed mineral manure, and yielded an average produce of 39 $\frac{1}{2}$ bushels of grain and 46 $\frac{1}{2}$ cwt. of straw.

Let me first call attention to plot 16*a*, which supplies the most striking instance of a decrease in soil nitrogen. This plot had received during thirteen years preceding the first soil sampling the highest dressing of artificial manure applied in the whole field, namely, 800 pounds of ammonium salts (mixed sulphate and chloride) per acre, with the mixed mineral manure, composed of superphosphate, with sulphates of potassium, sodium, and magnesium. During these thirteen years (1852-64) this plot yielded the largest crop in the field, the average produce being nearly 40 bushels of grain, with more than 46 cwt. of straw. The analyses of soil made in 1865 showed that the surface soil was richer in nitrogen than that of any other plot then analyzed, with the exception of that receiving farmyard manure. After 1864 the plot was left unmanured. The average unmanured produce during sixteen years is seen to have been only 13½ bushels, which is but 2¾ bushels more than that of plot 3, which has been unmanured since 1840. The diminution in the crop on this plot is seen to have been attended with a serious diminution in the nitrogen of the soil, which is 350 pounds per acre less at the end of the sixteen years of unmanured cropping. A person imperfectly acquainted with the subject might suppose that this loss of nitrogen was due simply to the disappearance of the ammonia previously applied to the soil in such large quantities. This is not so. The loss of nitrogen in the soil, like its gain, is an action belonging to the nitrogenous organic matter of the soil; this is proved by the fact that the carbon of the soil falls at the same time as the nitrogen and to a much greater extent.

The next most striking instance of a decline in soil nitrogen is presented by plot 5, which, like plot 16 and plot 3, had received no nitrogenous matter for many years. The diminution of the nitrogen on plot 5 is considerably less than on plot 16, and considerably more than on plot 3. The history of the field indeed shows that plot 5 lies between the two, for plot 3 has received no nitrogenous manure since 1840, plot 5 since 1851, and plot 16 since 1863. The running down of the nitrogen has thus continued much the longest on plot 3, and the annual diminution has now become a very small quantity.

INFLUENCE OF CROP RESIDUES.

Plots 10*a*, 11*a*, 7*a*, and 9*a* in Broadbalk field have some valuable lessons to teach us. The first three of these plots received every year the same dressing of ammonia, but with very different supplies of ash constituents. The amount of nitrogen (and carbon) found in the soils of these plots in 1881 was, however, distinctly different. The nitrogen in the soil thus stood in no apparent relation to the nitrogen in the manure, which we have already seen was equal in all cases. The figures in the table show, however, that the nitrogen in the soil did stand in a plain relation to the amount of crop grown on the land. Where the ammonium salts were applied without ash constituents (plot 10*a*) the produce was the

smallest, and so is the nitrogen in the soil, and this nitrogen, like the crop, is a diminishing quantity. Where superphosphate was supplied with the ammonia the crop is considerably increased, and so is the nitrogen of the soil, which has shown little change in sixteen years. Where the ammonia is used with a full supply of ash constituents the produce is the largest; the nitrogen, too, of the soil is largest and shows a tendency to rise.

We see here at once a relation between the amount of the crop and the rise or fall of the nitrogen in the soil. The quantity of nitrogenous matter in a surface soil can only be maintained when the crop grown on the soil reaches a certain annual amount. There is in fact an annual waste of the nitrogenous capital of the soil, and if the proportion of nitrogen in the soil is to be maintained there must be an equal annual addition of fresh nitrogenous organic matter; this is furnished to the soil in the form of crop residues, consisting of the dead roots, leaves, and stubble of a former crop, and the dead matter of weeds. When this crop residue is of large amount, as in the cultivation of red clover or in any case of green manuring, or when smaller residues are left untouched by the plow and allowed to accumulate, as in the case of pasture, the conditions for an increase in the nitrogen of the soil are present. When, on the other hand, the crop residue is *nil*, as in the case of a bare fallow, or very small, as upon unmanured land, there is either no or an insufficient replacement of the annual loss of organic matter in the soil, and the nitrogen of the soil consequently falls. The proportion of nitrogen in a soil can only be maintained when the supply of ash constituents is sufficient to furnish the necessary amount of crop and crop residue.

To return once more to the plots of Broadbalk, it will be noticed that the produce of wheat with nitrate of sodium is much larger than that with ammonium salts, both supplying about the same quantity of nitrogen; the nitrogen in the soil, however, shows no increase from this larger produce, and consequently greater crop residue. This is quite consistent with other results obtained with nitrate of sodium at Rothamsted. With the use of nitrate the rate of oxidation in the soil is in fact increased, and to this circumstance is due to a considerable extent its generally greater effect than ammonium salts as a manure.

We pass now to the—

CAUSES WHICH DETERMINE LOSS OF NITROGEN.

The nitrogenous organic matter contained in soils is for the most part an insoluble substance, a fact of the greatest importance for the maintenance of the fertility of soil. While in this condition it is of little use to the higher orders of plants among which our ordinary crops are included. To become available as plant food, it must be oxidized and rendered soluble, but as soon as this step is effected it becomes liable to be lost by drainage.

Not many years ago we would have been satisfied by explaining the oxidation which occurs in soil as due to a simple contact with oxygen; we now take a very different view of these changes. We know that the organic matter of the soil is split up and oxidized by means of living agents. A fertile soil is in fact teeming with life of many kinds. Many of these living agents are quite invisible to our eyes and yet are performing changes on a great scale, upon the accomplishment of which the growth of our food crops depends.

The living agents which attack the organic matter of soil may be classed as (1) animal life—worms and insects, (2) fungi, (3) bacteria. The worms, beetles, larvæ, etc., in a surface soil feed on the recently dead vegetable matter left by the crop or weeds which previously had possession of the soil; the carbon of this vegetable food is oxidized in their bodies and exhaled as carbonic acid, while the nitrogen is excreted in simple forms of combination. The fungi also feed on the nitrogenous organic matter of soil; carbon is oxidized in their cells and exhaled as carbonic acid, while their dead nitrogenous tissue restores to the soil a great part of the nitrogen which they had assimilated.

The “fairy rings” which occur in pastures furnish an excellent example of the action of fungi upon a soil rich in organic matter. It will be found that just outside the luxuriant ring of grass the soil is thoroughly permeated to a depth of about 6 inches by the mycelium of a fungus. The next year the luxuriant growth of grass occurs where the mycelium had grown the year before, a large quantity of the nitrogen of the soil having become available through the action of the fungus. At Rothamsted analyses have been made of the soil inside, upon, and quite beyond the borders of several fairy rings (*Trans. Chem. Soc.*, 1883, 208). It was found that the soil within the ring, which had fully undergone the successive action of the fungus and the following grass crop, contained on an average about 12 per cent less nitrogen and nearly 16 per cent less carbon than the soil outside the ring, which had not yet been attacked, the nitrogen and carbon in the latter soil being reckoned as 100. The loss of carbon to the soil was in some cases about 8,000 pounds per acre; the loss of nitrogen also amounted to several hundred pounds, only a part of which could be reckoned as recovered by the luxuriant crop of grass.

With the many highly important actions which bacteria produce within the soil, we are as yet only imperfectly acquainted. The production of ammonia and nitric acid from nitrogenous organic matter is among the most important of these changes. On the subject of nitrification I shall have a good deal to say in subsequent lectures, and would only now remind you that the same action which is so beneficial to our crops by changing inert organic matter into available plant food is also the means of placing in danger the nitrogenous capital of the soil, since nitrates are salts for which soil has no retentive power, and they are consequently removed with great ease when the soil is permeated

by rain. This loss of nitrates by drainage is to a considerable extent within the farmer's control; he has only to keep his land covered by a crop to prevent to a great extent the waste of nitrates.

The conditions which favor the complete oxidation effected by bacteria are aëration of the soil by tillage, the presence of a suitable amount of water and of calcium carbonate, and a high temperature. We shall consider the conditions favorable to nitrification more in detail by and by.

The action of the reducing bacteria is, as far as we at present see, entirely injurious to the purposes of agriculture, since by their means nitrates already formed are destroyed and the nitrogen in many cases returned to the atmosphere as gas. Of these bacteria we shall also speak in a future lecture. A water-logged soil furnishes the conditions most favorable to their action.

TENDENCY TO EQUILIBRIUM IN SOILS.

We have spoken earlier in this lecture of the natural limits to the accumulation of nitrogen in the soil; we can now, I think, perceive some of the causes of such limits.

The addition of organic matter to a soil either as crop or weed residue, or as farmyard manure, at once makes that soil a suitable home for the animal life, the fungi, and the bacteria whose function it is to reduce organic matter to the condition of inorganic matter. An increase of organic plant residue or manure thus creates some of the conditions favorable to its own destruction. The rate of oxidation in the soil is now no longer what it was; the oxidizing agents have increased with the material to be oxidized. If, therefore, a soil is laid down in pasture or receives an annual dressing of farmyard manure, the nitrogen in that soil will only increase so long as the annual increment of organic matter exceeds the annual decrement by oxidation. If this increment is a limited quantity it will be met before long with an army of destroyers competent to effect its destruction. The richest soils are thus the most liable to waste and demand the greatest exercise of the farmer's skill to preserve their condition.

When the conditions of the soil are changed, when the pasture is plowed up or the arable land is left without manure, there is at first a rapid loss of soil nitrogen, but the rate of loss soon diminishes. The organic matter most easily attacked has disappeared. The army of oxidizing organisms has been reduced by starvation. A partial equilibrium is established when the annual destruction of organic matter amounts to little more than the annual residue of crop and weeds; but an absolute equilibrium is reached only when the annual loss of nitrogen is equaled by the atmospheric supply. In every case nature seeks to establish an equilibrium.

We have now passed in rapid review the principal facts belonging to the subject. That we should acquire a complete knowledge of the

circumstances which determine the loss or gain of nitrogen in the soil is most desirable, and I have no doubt that many investigations will be made in America upon the subject. I wish, therefore, before I conclude to bring before you the method of soil sampling employed at Rothamsted, as without a method of this kind the examinations of soils will frequently lead to fallacious results.

THE ROTHAMSTED METHOD OF SOIL SAMPLING.

As the soil of a field is far from being a homogeneous substance, considerable pains must be taken if a truly average sample is to be obtained. As the soil varies in different parts of the field, samples have to be taken in many places. Since moreover the composition of a soil near the surface differs considerably with each inch of depth, it is imperative that the depth sampled should be accurately known and always adhered to if comparisons are to be made. It is for the same reason also essential that the sample taken should be in shape a cylinder or prism, all the cross sections of which shall have an equal area. Only when the sample is of this shape will the successive layers of soil be taken in their due proportion.

The plan I am about to describe has been in use at Rothamsted since 1856. A frame made of stout sheet iron, in shape a rectangular prism, open at top and bottom, is driven into the soil by repeated blows of a wooden rammer, till the soil has the same level inside and outside the frame. The soil inside the frame is then cut out and constitutes the sample of the first depth or surface soil. That the frame is accurately emptied is ascertained by trials with a wooden gauge of the same depth as the iron frame. If a sample of the next depth is to be taken, the soil is cleared away around the outside of the frame till the level is reduced to that of the bottom of the frame; the frame is then driven down again and the former operations are repeated.

Soil sampling at Rothamsted is usually carried down to three depths, but in a good many cases it has been carried down to twelve depths. The area of the sampling frame used for the first depth is usually 144 square inches (12 by 12 inches), a smaller frame, 6 by 6 inches, being used for the succeeding depths. The depth of each frame is 9 inches. Messrs. Lawes and Gilbert are of the opinion that 6 inches would have been a better depth to adopt for the samples of surface soil, but so much work has been done with 9 inches that it would now be very inconvenient to make any alteration.

The iron frame has a stout rim along its upper edge to increase its strength. The best sampling frame is made of cast steel; this form of frame needs no rim. Models both of the larger and smaller steel frames used at Rothamsted are before you, and I am instructed by Sir John Lawes to leave these models with your Department of Agriculture.

When the soil sampling is carried below the first depth care must be taken when digging around the frame that each depth of soil removed

is placed by itself, so that when the pit is filled in the soil may be returned to its proper position. A record must be kept of the place where the sampling was conducted, as a soil can not be accurately sampled twice in the same place.

Each sample of soil is weighed as soon as it is removed from the frame and is put into a bag by itself. When the soil reaches the laboratory it is at once broken up by hand into small pieces, and laid on paper trays, which are placed on the shelves of a store room kept at a temperature of about 55° C. till thoroughly dry; each sample is then returned to its bag. This immediate drying of the soil at a low temperature is essential if changes in the organic matter, and especially nitrification, are to be stopped. This practice dates at Rothamsted from 1877. After drying the soil it may be stored till leisure is found for further work. Each bag is then weighed. The soil is crushed and passed through a $\frac{1}{4}$ -inch sieve; the stones that do not pass through this sieve are weighed as stones. All that passes through the sieve is thoroughly mixed and a sufficient quantity is finely powdered for analysis. Mixed samples are prepared after the soil has passed through the $\frac{1}{4}$ -inch sieve or after it has reached the stage of fine powder.

In comparing the soils of different fields or of the same field at different periods of its history, it is very important to observe whether in each case there is the same weight of dry soil in the same depth. Differences of weight easily arise in the case of surface soils from alterations in the consolidation of the soil* or from the greater ease or difficulty with which the frame is driven down, due to the moist or dry condition of the soil and other causes. It is obvious that if a less weight of dry soil is included in one sample it really represents a shorter depth as compared with another sample of similar soil of greater weight. Now we have already seen that in the case of the surface soil a small alteration in depth will make a considerable difference in the percentage of nitrogen in the sample; the errors that may arise are thus important. A good example of the need of attention to the weight of soil in the depth sampled is supplied by the investigation upon the alteration in the composition of the soil of Dr. Gilbert's meadow (*Jour. Roy. Agr. Soc.*, 1889, 1). It is there pointed out that every increase in the proportion of the humic matter in the soil increases its porosity and decreases the weight of the soil in a given depth. A soil thus gradually becomes lighter as the proportion of nitrogenous organic matter in it increases, and it gradually becomes heavier when it is losing condition and becoming poor in nitrogen.

The extremely large and rapid gains and losses of nitrogen observed by Dehérain and other French investigators in field soils variously cropped, are possibly exaggerations of the truth, due to an imperfect

* Soils sampled for comparison should always be operated on when they are in the same condition. Arable soils are best sampled after the crop has been removed and before plowing.

method of soil sampling and to the fact that the same depth of soil is always reckoned to have the same weight. The French plan of soil sampling is to take a spadeful of the soil from several places. Now a spadeful of soil does not contain an equal proportion of the different layers through which the spade has penetrated. It contains, I think, a great preponderance of the surface layer. It is quite plain that if our soil samples contain an excess of the surface layer they must show much more rapid variations in composition than if a true proportion of the lower soil is always included. This error is intensified if the sample is always reckoned at the same weight, forgetting that as a soil increases in nitrogen it becomes lighter and as it loses nitrogen it becomes heavier.

LECTURE III.

NITRIFICATION.

Natural sources of nitrates—Artificial production of niter—Former theories of nitrification—Appearance of nitrous acid in bodies exposed to air—Nitrification produced by a living organism—Conditions necessary for nitrification—Substances capable of nitrification—Products of nitrification—The isolation of the nitrous organism.

By the word nitrification we commonly understand the production of niter. The chemist, however, has widened the meaning of the term so as to embrace the whole observed phenomena. In his use of the word, nitrification includes the production both of nitrates and nitrites.

NATURAL SOURCES OF NITRATES.

That niter is a natural product of certain soils and rocks was long known both in India and China. We have no certain evidence that niter was known in Europe before the thirteenth century. The nitrum of the Greek and Latin writers would seem from their description of it, to have been not niter, but a crude form of alkali. The earliest name given to niter by European writers is *Sal petrosum* or *Sal petrae*, from which we obtain our common word saltpeter.

I need not mention in detail the various localities which have in former times been famous for their yield of niter. Of these certain districts in North India have been, from a commercial point of view, the most important. These districts still continue to export a considerable amount of saltpeter, notwithstanding the large manufacture now carried on in Europe from nitrate of soda and German potash salts.

The niter-yielding districts of India have a porous, alluvial soil, containing limestone concretions; the water level is in every case far beneath the surface. The collection of niter is made only from the soil of old villages. The sorawallah or native niter manufacturer comes around the village daily and scrapes off a thin layer of soil wherever he observes a white efflorescence on the surface; the places where he especially finds such appearances are in the neighborhood of the house drains or round the cow sheds. From these scrapings of soil he prepares a crude saltpeter by extraction with water and crystallization.

ARTIFICIAL PRODUCTION OF NITER.

The consumption of niter in Europe for the manufacture of gunpowder has, I need hardly say, been enormous, larger in fact than could be met by the imports from India and other niter-yielding countries. There arose in consequence a necessity for a home production of niter. This necessity was most severely felt in the case of France, Germany, and Sweden, whose imports of niter were small and liable to be cut off in time of war. Glauber, in the seventeenth century, was apparently the first who succeeded in producing niter by artificial means. It was soon found that the earthen floors of stables, farmyards, and dwelling houses, when mixed with wood ashes and extracted with water, yielded more or less saltpeter. In France the right to remove these saltpeter earths once every year was granted to certain manufacturing companies, and every parish was forced to make an annual contribution of wood ashes for the purpose of the manufacture.* The intolerable annoyance and oppression resulting from such a state of things we can now hardly realize. These saltpeter laws remained in force till within a few years of the great Revolution. The manufacture of niter was then placed in the hands of a scientific commission, of which Lavoisier was a member, and great improvements were carried out. In Sweden, down to a much later period, every farmer was obliged by law to furnish the Government with a certain weight of saltpeter every year as a part of his taxes.

We need not describe in detail the particular methods for the production of niter finally adopted as the result of much experience in France, Germany, and Sweden; these will be found described in the works of Berzelius, Dumas, and Boussingault. The general mode of proceeding was in all cases much the same. First, a porous earth, rich in humus, was prepared. This was artificially enriched both with nitrogenous and calcareous matter, and was then kept for a long time in a certain favorable condition of moisture and aëration. In some cases successive crops of niter were obtained by scraping the dried surface of the heap of soil, but in all cases the whole mass was finally extracted with water. Under the French mode of proceeding the result was considered satisfactory if at the end of two years 1,000 pounds of earth yielded 5 pounds of crude saltpeter. The washed earth of an old niter bed formed the best material for the construction of a new one.

During the many years in which the manufacture of niter was of great national importance, much experience was gained as to the conditions most favorable to nitrification. The richness of the soil in nitrogenous matter; the presence of calcium carbonate or some other base; the aëration of the soil; the presence of a certain happy proportion of water, which must be diminished as the soil became rich in niter; and

* Calcium nitrate was the form in which the nitric acid usually occurred in the niter earths; by treating this with a solution of potassium carbonate, obtained by extracting wood ashes with water, potassium nitrate (saltpeter) was produced.

lastly, a summer temperature were all recognized as conditions favorable to nitrification. On the other hand the presence of fresh organic matter or the growth of molds was known to be injurious. Great efforts were made by scientific men to understand the chemistry of the process, as it was obvious that if the manner in which nitrification took place was accurately known considerable improvements in the mode of conducting the process might be expected. We will very briefly notice the various theories which have been held.

FORMER THEORIES OF NITRIFICATION.

As niter is found as an efflorescence on the surface of the nitrifying matrix, it was assumed by the alchemists that niter was of aerial origin. John Davy, as the result of his examination of the niter-yielding caverns in Ceylon, concluded that the nitric acid was formed from the nitrogen and oxygen of the air. Longchamp fully enunciated this theory. He regarded the combination of the atmospheric nitrogen and oxygen dissolved in the water of moist, porous bodies as the only source of nitric acid. Cloez in his excellent lecture on nitrification (*Leçons de chimie et de physique professées en 1861 à la Société Chimique de Paris*), considers that such a combination of nitrogen and oxygen is induced by the presence of other matters undergoing oxidation, and believes that this oxidation of the nitrogen of the atmosphere is one of the sources of the nitric acid produced during nitrification in the soil. Many chemists have in like manner explained the nitrification of organic matter by assuming that this matter evolves nitrogen during its decomposition and that this nitrogen in its nascent state is oxidized by the oxygen of the air, which may be present in a condensed state on the surface of porous bodies. This explanation is the one given by Hofmann (*Exhibition Report*, 1862, 47). The above theories have also been modified by the substitution of ozone for oxygen. This was the view once held by S. W. Johnson. Ozone is assumed to be formed during the oxidation of the organic matter of the soil; this ozone is then supposed to attack the free nitrogen present and produce nitric acid.

The truth or fallacy of the theory of nitrification we have just sketched is of the greatest importance to practical agriculture, for if the nitrogen of the air can be oxidized to nitric acid in the soil, it is clear that we have in nitrification an actual creation of plant-food. The weight of chemical evidence is, however, certainly against the view in question. Nitrogen and oxygen certainly combine at a very high temperature, as that given by the electric spark, or that produced by heating platinum to its melting point, or by the combustion of hydrogen in oxygen; but at somewhat lower temperatures, as that of hydrogen burning in air, no nitrous or nitric acid is produced if the materials used are perfectly free from ammonia (Wright, *Trans. Chem. Soc.*, 1879, 42). Porous bodies also appear to be without effect in inducing the combination of nitrogen and oxygen. Neither spongy platinum nor

charcoal is capable of bringing about the combination of nitrogen and oxygen, even at a high temperature. Moreover, according to Schlösing's recent experiments (*Ann. de la Science Agronomique*, 1884, 1), soil is not a substance capable of condensing gases in its pores, but all the gases it contains occupy their normal volume. The best proof that the nitrogen of the atmosphere takes no part in the process of nitrification is, however, afforded by the experiments of Boussingault (*Compt. rend.*, 76, 22). He placed weighed quantities of soil of known composition in large glass vessels, which were then perfectly closed and kept in a cellar for eleven years. At the end of this time much nitric acid was found in the soil, but the total nitrogen in the soil had somewhat diminished. There had thus been no gain from the air in the vessel.

A second group of theories regards the oxidation of ammonia as the source of the nitric acid in soils; this view was partly held by several of the older chemists, but was first strongly insisted upon by Kuhlmann. He proved by many experiments that ammonia could be readily converted into nitric acid by means of powerful oxidizing agents, and concluded that through the agency of the porous bodies contained in soil the oxidation of ammonia might be effected and nitric acid produced. This theory has been modified by some by assuming that the oxidation in question is induced by the disposing influence of other oxidizing actions, or is brought about through the agency of ozone or of hydrogen peroxide. A further modification of the theory regards ferric oxide as the agent which accomplishes the conversion of ammonia into nitric acid. This latter view has been held by P. Thenard, Knop, Haarstick, and Pesci.

It is quite true that ammonia can be oxidized by ozone, by hydrogen peroxide, and by other powerful agents, but no proof has been offered that such agents are present in the soil. That ordinary oxygen at ordinary temperatures is capable of oxidizing ammonia has certainly not been proved. The power of ferric oxide to convert ammonia into nitric acid has also been denied both by Millon and Storer.

The fact that blood and other nitrogenous substances may be oxidized by the action of an alkali and a permanganate and nitric acid produced, is equally without any bearing on the question of nitrification in soil.

It is curious now to reflect that chemists were undoubtedly satisfied with the theories of nitrification we have just noticed. Later researches, as you are aware, have shown that these theories were entirely beside the mark. Before laying before you the modern theory of the process of nitrification, let me pause for a moment and call your attention to some facts which explain, I think, a good deal of the confidence once felt by able chemists that a combination of the nitrogen and oxygen of the air in the presence of water was the real origin of the nitrates found in soils. Their conclusions were indeed apparently justified to some extent by their experiments.

APPEARANCE OF NITROUS ACID IN BODIES EXPOSED TO AIR.

According to Schönbein, pure water can not be evaporated without the residue being found to contain ammonium nitrite. It is quite true that if pure water is exposed to air it is found after a time to contain nitrites. It is also quite true that if water be evaporated over a gas flame, the quantity of nitrites found after concentration to a small bulk is still more considerable. Other experimenters have found that moist chalk gains nitrates and nitrites when exposed to air. This is again an undoubted fact. The true explanation of all these results is, however, quite different from that which the original experimenters supposed. The results obtained are in reality due to the following facts: (1) That atmospheric air contains a minute quantity of nitrites and nitrates; (2) that considerable quantities of nitrites are formed during combustion if the fuel or the atmosphere in which it is burned contains ammonia.

The occurrence of nitrites in the air was one of the subjects I experimented on while working in the Rothamsted laboratory (*Trans. Chem. Soc.*, 1881, 229). Pure distilled water exposed to air in the open field gained a distinct trace of nitrous acid in three days. In the air of the laboratory a larger amount was gained after two or three hours' exposure. The concentration of water in a retort was not attended with the appearance of nitrous acid, but concentration in an open basin always resulted in the appearance of nitrous acid in the residue. The amount of nitrous acid was much the greatest when coal gas was employed as fuel, less when an alcohol flame was the source of heat, and far less when the evaporation was conducted over steam. The presence of nitrites in the atmosphere and especially in rooms where coal gas is burnt, must always be taken into account when conducting investigations on nitrification.

NITRIFICATION PRODUCED BY A LIVING ORGANISM.

We have now, I think, cleared the way for the consideration of the most interesting part of our subject, the production of nitrates and nitrites by living organisms.

A study of the phenomena of fermentation and putrefaction had established the remarkable fact that these profound chemical changes were entirely due to the action exerted by living agents upon substances occurring in the media in which they lived. The living beings which possessed this wonderful chemical energy were simple cells—yeasts, or bacteria—extremely minute in size, but making up for this disadvantage by their enormous number, and the extreme rapidity with which under favorable conditions their numbers were increased. Some of the actions determined by these minute organisms were of a purely oxidizing character, as for example the oxidation of alcohol into acetic acid in the production of vinegar. It occurred to Pasteur that possibly the production of nitric acid in soil might be due to a similar agency. He threw out this idea in 1862, but no investigation was then made

upon the subject. In 1873 A. Müller remarked that while the ammonia of sewage often changed rapidly into nitric acid, solutions of ammonia and of urea prepared in the laboratory remained unaltered. He suggested that the sewage probably contained a ferment which was absent from the pure solutions prepared in the laboratory. He took no steps, however, to show that the nitrification which took place in sewage was a process possessing the characters of fermentation.

To the French chemists Schlösing and Müntz belongs the credit of establishing by experiment the true nature of nitrification. Their first paper on the subject appeared early in 1877 (*Compt. rend.*, 84, 301), or about fourteen years ago. They wished to ascertain if the presence of humic matter was essential to the purification of sewage by soil, and for this purpose they conducted an experiment in which sewage was passed slowly through a column of sand and limestone; under these circumstances complete nitrification of the sewage took place. They then allowed chloroform vapor to fall for some time on the top of the column, the sewage passing as before. Nitrification now entirely ceased and was not renewed for seven weeks, though the supply of chloroform was suspended. A small quantity of a nitrifying soil was then shaken with water and the turbid extract poured on the top of the column. Nitrification at once recommenced as strongly as before. To appreciate the force of the experiment we must recollect that Müntz had previously shown that chloroform was a means of distinguishing between the action of a simple ferment, as diastase, and a living organism, as yeast, the chloroform having no influence on the work of the unorganized ferment, while it immediately stopped the activity of a living agent.

At the time when these results were made public I was occupied in the Rothamsted laboratory with an investigation on the amount of nitrates present in soils of known history. The immense importance of the new theory of nitrification propounded by Schlösing and Müntz led me at once to commence experiments to test the truth of their conclusions. The experiments first made were designed to answer two questions: (1) Would nitrification in an ordinary soil be suspended by the presence of antiseptic vapors? (2) Could the power of nitrification be imparted to a suitable medium by seeding it with nitrifying or nitrified matter? The trials were made as follows: A sifted garden soil, containing a known amount of nitrate, was placed in a series of wide glass tubes, through which air, freed from ammonia, was daily drawn. One of the tubes of soil received air without addition; another received with the air a little chloroform vapor; in the case of a third, the air was supplied with a little vapor of carbon disulphide. After passing air through these soils for more than a month the amount of nitrate present was determined. In one series of trials the soil through which air alone had been passed was found to contain nearly six times its

original amount of nitrate; in another case the increase was still greater, while the soil receiving with the air the vapor of chloroform or carbon disulphide showed no distinct increase in the nitrate originally present. The antiseptic vapors had thus effectually prevented nitrification.

To furnish an answer to the second question, a weak solution of ammonium chloride, with the addition of some potassium phosphate and calcium carbonate, was placed in four pint bottles; two were placed in a window and two in a dark cupboard. To one under each condition was added 1 gram of fresh pasture soil. After some time the solutions were examined. The ammonia in the solution seeded with soil and kept in darkness, was found to be completely nitrified; the other solutions remained unchanged. From the solution which had nitrified a few drops were taken and introduced into the two solutions which had hitherto remained unseeded. The result, as before, was that the solution in darkness nitrified while that in the light did not.

The previous results of Schlösing and Müntz were thus confirmed. It was shown that (1) the power of nitrification could be communicated to mediums which did not nitrify by simply seeding them with a nitrified substance; (2) the process of nitrification in garden soil was entirely suspended by the presence of the vapor of chloroform or carbon disulphide.* These two facts taken together clearly pointed to a living agent as the cause of nitrification. It was also shown that light is unfavorable to its action.

Since these earliest experiments a good deal of additional proof has been furnished by Schlösing and Müntz and by other investigators, showing that the process of nitrification, both in soils and waters, is undoubtedly the work of a living organism. The limits of temperature within which nitrification is possible, the necessity for the presence of plant food, the fact that the power of nitrification is lost if the nitrifying material is raised to the temperature of boiling water, all these confirm the conclusion previously arrived at from the action of antiseptics and the transmission of the faculty of nitrification by seeding.

I must not attempt to give an historical account of the numerous investigations which have been made on the subject of nitrification since the true nature of the process was discovered by Schlösing and Müntz. I can only hope to lay before you the principal results which have been arrived at. As Rothamsted work is my special subject in these lectures, I may mention that investigations on nitrification have engaged a large part of my time in the Rothamsted laboratory. I must not, however, confine myself to Rothamsted results if I am to give you a fairly complete account of the developments of this extremely interesting inquiry.

* Phenol vapor was found at the same time to hinder nitrification; it did not, however, wholly suspend it, a result apparently due to the failure of the vapor to penetrate the whole column of soil.

CONDITIONS NECESSARY FOR NITRIFICATION.

The first condition necessary for the activity of a living organism is food. The food of plants and animals is in some respects different, but both are alike in requiring a supply of certain mineral substances for their nourishment. One of the most essential constituents of this mineral food is phosphoric acid. Without phosphates there can be neither growth nor life. It is therefore a corroboration of the modern theory of nitrification when we find that ammoniacal solutions are not susceptible of nitrification when phosphates are absent. A solution containing a pure ammonium salt is indeed readily nitrified if a little soil is introduced. In this case the soil which has been added supplies the necessary food for the organism. But if from this solution when nitrified a second ammoniacal solution containing no phosphoric acid is seeded, nitrification will proceed much more slowly; and if from this second culture the attempt is made to start a third, it will probably be found that though nitrification may commence it will never be completed. What effect the absence of other ash constituents may have on the process of nitrification has not yet been ascertained.

It has hitherto been held that organisms destitute of chlorophyll must be supplied with carbon in some organic combination. For the nutrition of fungi, for example, some carbonaceous substance, as sugar, tartaric acid, or humus, must be present; the fungi appropriate this carbonaceous matter, partially oxidize it, and construct from it the carbonaceous substances which form their tissues. It has been shown in a multitude of cases that bacteria may be nourished in a similar way. The nitrifying organism can apparently feed upon organic matter, but it can also apparently with equal ease develop and exercise all its functions upon purely inorganic food. This fact is perhaps to the physiologist the most important, the most startling, that has appeared in connection with the subject of nitrification.

Isolated cases occurred in my own early experiments in which nitrification took place without the intentional addition of organic matter to the solutions. The experiments of Dr. J. M. N. Munro (*Trans. Chem. Soc.*, 1886, 651) supplied some very distinct examples of this fact, which led to further attention being given to the subject. I was able to substantiate Dr. Munro's results and to show that nitrification could be carried on readily for many successive generations in inorganic fluids contained in glass-stoppered bottles.* None of these results, however, afforded any proof that the nitrifying organism was entirely independent of a supply of organic food, as no special precautions had been taken to exclude traces of organic matter. To Winogradsky belongs the credit of supplying actual proof of the fact in question.

* P. F. Frankland has made a much longer series of cultures in inorganic solutions, but in bottles closed with cotton-wool stoppers, from which organic matter might possibly be derived.

Winogradsky (*Ann. de l'Institut Pasteur*, 1890, 268) prepared vessels and solutions carefully purified from organic matter, and these solutions he sowed with the nitrifying organism. Finding that under these conditions the nitrifying organism increased enormously and displayed its full vigor, he proceeded further to determine the amount of carbonaceous organic matter formed in solutions after the introduction of the organism. By making the nitrification intensive, he was able to obtain considerable quantities of carbon from the nitrified solutions by the process of wet combustion. In his third memoir he publishes figures which apparently show a close relation between the amount of nitrogen oxidized and the amount of carbon assimilated; the ratio is about 35:1.

That an organism unprovided with chlorophyll and growing in darkness should be able to construct organic matter out of ammonium carbonate is certainly a fact of the highest interest. The process would seem to us an impossible one but for the energetic oxidation of ammonia which forms part of it; by this oxidation so much energy is developed that the nutrition of the nitrifying organism by ammonium carbonate becomes part of a strongly exothermic reaction. Winogradsky suggests that the ammonium carbonate in the first instance probably gives rise to an amide, and reminds us that this is what happens in the animal body, where ammonium carbonate is converted into urea.

Since the publication of Winogradsky's results I have employed the acid carbonates of sodium and calcium with distinct success as ingredients of an ammoniacal solution undergoing nitrification, the rapidity of nitrification being considerably increased by this addition; this favorable result appeared with equal distinctness during the conversion of nitrites to nitrates.

The next condition of nitrification we have to mention is the presence of oxygen. Schlösing (*Compt. rend.*, 77, 203, 353) has determined the rate of nitrification in a moist soil kept in atmospheres containing various proportions of oxygen. When oxygen was entirely absent and nitrogen only supplied, a reduction of the nitrates originally present took place, nitrogen gas being evolved. When the atmosphere contained only 1.5 per cent of oxygen a considerable amount of nitrification occurred. With 6 per cent of oxygen the nitrates produced were rather more than doubled. With 16 to 21 per cent of oxygen the nitrates obtained were more than four times as much as when the smallest proportion of oxygen was employed. When the proportion of water in the soil was raised from 16 to 24 per cent the effect of higher proportions of oxygen became relatively less. The oxygen acts apparently as dissolved oxygen; an increase in the proportion of water in the soil will thus, up to a certain point, have the same effect as an increase in the proportion of oxygen. The great influence of tillage in promoting nitrification in a clay soil is doubtless due in great measure to the more perfect aëration of the soil which is thus effected.

A further condition of nitrification is the presence of a base with which the nitric acid when formed may combine. This condition is quite essential. Nitrification can only take place in a feebly alkaline medium. A solution of sulphate or chloride of ammonium may be enriched with phosphates and the other necessary constituents of plant food, but the solution will be unaffected by any seeding with the nitrifying organism unless some salifiable base is present. For the same reason nitrification will not occur in peat, or in peaty water, or in some forest soils, in which the humic acids are present in excess. Upland waters are for this reason generally free from nitrates.

In a solution of ammonium carbonate, nitrification will take place till one half of the ammonia is oxidized and will then stop. The ammonia has now been converted into ammonium nitrite or nitrate, and all the available base is exhausted. For the same reason nitrification will only proceed in diluted urine till one half of the nitrogen is oxidized (*Trans. Chem. Soc.*, 1884, 654). For the nitrification of ammonium salts, urea, or other nitrogenous matter to be complete, some salifiable base must be present. The substance which usually plays this part in soil is calcium carbonate. A soil which contains little or no available base is sure to be very deficient in fertility. Such soils are greatly benefited by dressings of chalk or lime.

Although an alkaline condition of the medium is essential for nitrification, the presence of anything beyond a small proportion of soluble alkali is a hindrance to the process, and a large amount will prevent the action altogether. The prejudicial influence of the alkali carbonates was first pointed out by Schlösing and Müntz (*Compt. rend.*, 89, 1075), and has since been fully studied at Rothamsted (*Trans. Chem. Soc.*, 1884, 653). It was found that the presence of 320 mgs. per liter of disodium carbonate distinctly retarded nitrification. With an increased quantity of disodium carbonate the commencement of nitrification was still further retarded, and with 960 mgs. per liter nitrification was only barely possible. Monosodium carbonate (commonly known as bicarbonate) was found to be far less prejudicial. Indeed quantities up to 4 grams per liter increased the speed of nitrification, but with 6 grams per liter nitrification was much retarded. A similar distinction was observed between the carbonates of ammonium, an increase in the proportion of the carbonic acid diminishing the injurious effect of the salt. The strongest solution of ammonium carbonate that was nitrified had at the commencement of nitrification an alkalinity equal to 447 mgs. of ammonia per liter. Nitrification did not occur in this case for ninety-six days.

The strength of a urine solution which can be nitrified is limited by the proportion of ammonium carbonate which will be formed from the urea during the first stage of the action. When urine in different degrees of dilution was treated with soil, 1 gram of soil being added to 100 c. c. of diluted urine, nitrification commenced in the 1 per cent

solution in 11 days, in the 5 per cent solution in 20 days, in the 10 per cent solution in 62 days, in the 12 per cent solution in 90 days. The alkalinity of the last-named solution when nitrification commenced was equal to 447 mgs. of ammonia per liter. A solution with an alkalinity of 500 mgs. of ammonia per liter is apparently unnitrifiable. This part of the subject is of considerable practical importance, as it shows the necessity of a proper dilution of liquid manure before it is applied to the land. Solutions of ammonium carbonate, considerably richer than those I have just named, can, however, be nitrified when poured on a fertile soil, a part of the ammonia being doubtless removed from the solution by the chemical action of the soil.

In connection with these facts we may call to mind the observation of Boussingault, that liming a soil diminishes the production of nitrates. The alkalinity of limewater is indeed about twice as great as that shown by the Rothamsted experiments to be the maximum beyond which nitrification will not occur. A heavy dose of lime applied to land may thus suspend for a time the process of nitrification in the surface soil, but this action will soon cease as the lime unites with carbonic acid, and the final result will be favorable to nitrification if the land was originally deficient in lime.

By a simple chemical expedient it is possible to diminish the alkalinity of liquid manure or other liquids containing alkali carbonates, and thus render them suitable for nitrification; this may be done by the addition of gypsum (*Trans. Chem. Soc.*, 1885, 758). When a sufficient amount of gypsum is present solutions containing 50 per cent of urine become nitrifiable; with very strong solutions, however, nitrification is very slow in beginning. The gypsum acts by converting the alkaline ammonium carbonate into neutral ammonium sulphate, calcium carbonate being precipitated. The calcium carbonate is subsequently redissolved as nitrification progresses. The action of gypsum we have just noticed probably explains its beneficial effects on nitrification observed by Pichard and attributed by him to an alternate reduction and oxidation of the gypsum, of which, however, he gives no proof. Gypsum would probably be found a valuable ingredient of niter beds. It must also increase the oxidizing power of the soil used in earth closets. In cases where strong sewage is to be treated by application to land, the addition of gypsum would avoid the necessity of great dilution, and probably would enable oxidation to be effected by a smaller area of land. In agriculture the activity of farmyard manure would probably be increased by the addition of gypsum to the soil.

A further essential condition of nitrification is that the materials shall be kept at a favorable temperature. It is one of the characteristics of the nitrifying organism that it is capable of exercising its functions at a lower temperature than is required by most organisms. Experience at Rothamsted shows that nitrification takes place pretty freely in the soil during an ordinary English winter. In one series of laboratory

experiments a considerable rate of nitrification was observed in solutions the mean temperature of which was between 3° and 4° C. (37° and 39° F.). At summer temperatures, however, nitrification becomes far more active; of this we shall have an excellent illustration when we speak of the nitric acid produced in the soils of the Rothamsted drain gauges. According to Schlösing and Müntz, nitrification becomes really active at 12° (54° F.) and rapidly increases in energy up to 37° (99° F.), at which point nitrification is ten times more speedy than at 14° (57° F.). Above 37° the rate of nitrification rapidly diminishes, and is less at 45° (113° F.) than at 15° (59° F.). At 50° (122° F.) very little nitrate is produced, and at 55° (131° F.) there is absolutely no action. This series of temperature observations by Schlösing and Müntz has not, as far as I know, been confirmed by other investigations. At Rothamsted I failed to start nitrification in a solution maintained at 40° (104° F.).

The nitrifying power of soil is not only destroyed at a high temperature, but it may also be destroyed by drying the soil thoroughly at the temperature of the air.

The absence of strong light appears to be another condition necessary for nitrification. I have generally failed to nitrify solutions placed in a window. In one instance a solution in which nitrification was half completed was placed in a south window and exposed to sunshine. No further increase of nitric acid took place in this solution during a fortnight. At the end of this time the bottle was placed in darkness and nitrification resumed.

The presence of considerable quantities of saline matter, according to Schlösing and Müntz, does not hinder nitrification.

SUBSTANCES SUSCEPTIBLE OF NITRIFICATION.

Our knowledge of the nitrifying process is chiefly derived from a study of the action of soil in its natural solid condition and from a study of the chemical changes which take place in solutions to which a small quantity of soil has been added. Little has yet been done to ascertain the action of the nitrifying organisms when in an isolated condition.

A good deal of experience has accumulated respecting the nitrification of substances applied to soil for the purposes of manure. We know that not only soft animal tissues, but the nitrogenous matter of bone, wool, and horn are nitrified in the soil. Vegetable matters are equally nitrifiable, as is shown by the nitrates found at Rothamsted when rape cake has been employed as manure, and by the results obtained by Müntz respecting the nitrification of green crops plowed into the soil. The humic matter of a surface soil is clearly nitrifiable, and experiments have shown that the same is true of the more nitrogenous organic matter of a clay subsoil.

Experiments conducted in solutions in the laboratory show that ethylamine, thiocyanates, and gelatin are nitrifiable (Munro, *Trans.*

Chem. Soc., 1886, 633), as well as urea, asparagine, and the albuminoids of milk and rape cake (*Ibid*, 1884, 650). In all these cases, however, other species of bacteria have been present besides the nitrifying organisms, and it is impossible to tell how far the action of the latter has been helped by a preliminary attack upon these nitrogenous bodies made by other bacteria. In fact in all the cases of nitrification produced by soil which have been thoroughly studied, the formation of ammonia has been found to precede the formation of nitrous or nitric acid.

I have made a few trials of the action of the isolated nitrous organism upon urea, asparagine, and milk solutions. In all these cases nitrous acid was certainly produced in very distinct quantity, but the action appears sluggish, and by no means equal to that exerted by the mixed organisms of soil. The subject, however, requires further study.

The oxidizing power of the microorganisms of soil is not confined to the oxidation of ammonia or of organic matter. Müntz has shown that soil is capable of oxidizing iodides to hypoiodites and iodates, and bromides to hypobromites and bromates. This is a very important result, and seems to indicate that nitrification is part of a general oxidizing action, and that we must not assume that nitrites or nitrates are produced because they are in themselves of advantage to the organism. We have already seen, however, that the *energy* resulting from oxidation must render important service to the organism by enabling it to appropriate the carbon of carbonic acid.

THE PRODUCTS OF NITRIFICATION.

When nitrification occurs in soil the products of change are nitric acid, carbonic acid, and water. Schlösing has shown that even during the rapid nitrification which occurs in a soil which has been enriched with ammonium salts, more oxygen is consumed than is required for the nitric acid produced; carbonaceous matter is thus oxidized at the same time as ammonia. We can not, however, at present state certainly that the carbonaceous matter of the soil is attacked by the same organisms which produce nitric acid.

Nitrous acid does not appear in soils as a product of nitrification; the drainage waters from the very variously manured plots in the Rothamsted wheat field rarely contain more than a trace of nitrous acid. Nitrous acid may indeed be produced in soils (under certain conditions) as a product of reduction, but of this we shall speak by and by.

When a small quantity of soil is added to a cold, weak ammoniacal solution (0.08 gram ammonium chloride per liter), supplied with phosphates, etc., the nitrification that occurs is generally purely nitric. If the solution is much stronger, and especially if the temperature is raised to 30°, large quantities of nitrous acid are formed; indeed the action at first may be wholly nitrous. But when the ammonia has disappeared or greatly diminished, the nitrites are converted into nitrates. This conversion generally takes place very speedily when it commences, but

often a considerable interval elapses between the completion of the change into nitrites and the commencement of the change into nitrates. That soil possesses ample powers of oxidizing nitrites may be readily proved by introducing a little soil into a dilute solution of potassium nitrite supplied with phosphates, etc.; if this solution is placed in the dark at a suitable temperature the nitrites will be speedily changed into nitrates.

The result of the action of soil upon ammonia and also upon other nitrogenous matter is thus in every case to form nitrates, if the soil is allowed to complete its action; it is evident, however, that the operation may occur in two stages. When in place of using soil we employ a nitrified solution (originally seeded with soil) for starting nitrification in another solution, the same course of action occurs that we have just described. If, however, we continue to make successive cultures in ammoniacal solutions, the action gradually becomes more nitrous in character even in the case of cold, weak solutions, and sometimes the power of forming nitrates is entirely lost. This separation of a purely nitrous agent occurred in my experiments as early as 1879. When other ammoniacal solutions are seeded from such a source only nitrites are produced, and this is the case however small is the depth of the solution and however large is consequently the surface exposed to air. The same production of nitrites occurs if diluted urine or solution of asparagine or milk is nitrified by the agent in question. The nitrites thus produced are quite permanent.

The existence of a purely nitrous agent was not at first admitted by other workers on the subject. Some, as Schlösing and Müntz, regarded the production of nitrites as simply due to the presence of conditions unfavorable to full oxidation, as too great depth of liquid, too low temperature, etc.; to which they afterwards added another circumstance—a too alkaline condition of the solution. This explanation is negatived by the fact that we may take two perfectly similar ammoniacal solutions, and place them under identical conditions, and by seeding them from different sources we may have a purely nitric reaction produced in one and a purely nitrous reaction in the other, a result which plainly indicates that it is the nature of the agent and not the circumstances under which it acts, that determines the result of nitrification. Other investigators, as Gayon and Dupetit, have considered that nitrites are in all cases products of reduction. This explanation is also negatived by the fact that the production of nitrites proceeds with perfect success in solutions containing no organic matter and also, as Dr. Munro has shown (*Chem. News*, 56 (1887), 62), is not increased by the previous addition of nitrates.

I was disposed at first to regard the nitrous agent which I have described as a degenerate form of the nitrifying organism of the soil. The original nitrifying organism was supposed to be capable of oxidizing ammonia to nitrate. By long-continued cultivation in ammoniacal

solutions it lost a part of its chemical energy and became capable of producing nitrites only. This explanation seemed reasonable from a chemical point of view, as, regarded from the standpoint of thermochemistry, the conversion of nitrite to nitrate is a more difficult operation than the oxidation of ammonia to nitrite. The explanation was also accordant with well-known facts in the history of bacteria, which in many cases lose both chemical and physiological properties by long cultivation in artificial media. We shall see by and by that the facts admit of another and more satisfactory explanation.

Very many experiments were made before I ascertained what were the conditions which determined the separation of a nitrous agent from soil. The first idea, that the loss of power to produce nitrates was determined by the *age* of the culture, was not always found to be true, in fact. Age alone does not necessarily bring about the change in question. There appear to be two factors favorable to the separation of this nitrous agent: (1) The origin of the soil used has considerable influence; solutions seeded from a pasture soil will lose the power of producing nitric acid far more readily than solutions seeded from an arable soil. (2) The alkalinity of the ammoniacal solution has a still greater influence. The latter circumstance enables us to prepare the purely nitrous agent at any time without fail. In the early experiments the alkalinity was produced by the addition of ordinary neutral sodium carbonate to the ammoniacal solution at the rate of 0.32 gram per liter. This proportion was sufficient to leave the solution alkaline after the complete nitrification of the ammonia. The simplest plan, however, is to conduct the nitrification in a solution of ammonium carbonate. If a solution containing 0.25 gram of ammonium carbonate per liter is employed,* two or three successive cultivations will suffice to eliminate the power of producing nitrates and place in our hands the purely nitrous agent.

THE ISOLATION OF THE NITROUS ORGANISM.

As soon as the fact had been established that nitrification was the work of a living organism, it became important that this organism should be isolated and its properties studied; until this was done it was impossible to tell whether the whole series of chemical changes which occur during nitrification was accomplished by a single agent or whether different stages in the work were performed by different organisms. The inquiry was of course much complicated by the fact that soil contains a multitude of organisms, concerning the character and properties of which we possess but little information.

Schlösing and Müntz were the first to attempt the isolation of the nitrifying organism. Their method was to start nitrification in a weak, sterilized sewage by the addition of a few particles of soil, and when

* The solution I have employed contains ammonium carbonate 0.25 gram, potassium phosphate 0.04 gram, magnesium sulphate 0.02 gram, and calcium sulphate 0.02 gram per liter.

nitrates appeared in this solution to seed with it another sterilized solution. After a series of cultures made in this way, they tell us that only one kind of organism appeared on examination with the microscope. This organism they describe as consisting of very small, round, or slightly elongated corpuscles, occurring either singly or two together.

The identification of the nitrifying organism by Schlösing and Müntz has not been received with much confidence by bacteriologists. Their method of isolation was one hardly likely to be successful in the case of a slowly multiplying organism, like the one in question; moreover they have told us nothing about the characters of its growth in various media, or about its chemical powers when acting strictly alone. My own impression is that both Schlösing and Müntz observed and described the nitrifying agent, but that it is very doubtful whether they possessed it in a pure state.

The question remained in this state for several years. Many microscopists undoubtedly observed the organism; indeed under certain conditions masses of it become visible to the naked eye. If nitrifying cultures are made in inorganic, ammoniacal solutions, or at least in solutions containing very little organic matter, certain gelatinous masses* are observed at the bottom of the vessel as the culture becomes old; these are actually the organism in its zoöglæa condition.

When Koch's method of growing bacteria upon the surface of a nutrient jelly came into use, the isolation of individual species was made far easier than it was before, and the separation of the nitrifying organism was again attacked by several investigators. An immense deal of time and labor has, however, been spent in vain, for though probably considerably more than one hundred species of bacteria† separated by culture on gelatin have been tested as to their power of causing nitrification, not one has been certainly found to possess this property. It has indeed been found that all the organisms which have been obtained from nitrifying solutions by growth on gelatin or agar-agar, exhibit no nitrifying power, even when the jelly upon which they have been grown is merely a solidified solution of known nitrifying capacity. The organisms growing on gelatin are also generally bacilli, while the nitrifying solution, if it be a tolerably pure one, contains chiefly cocci. We now know how these facts are to be explained—the nitrifying organisms will not grow on gelatin.

The first successful attempt at isolation was made by Dr. P. F. Frankland (*Phil. Trans. Roy. Soc.*, 1890, B. 107). He first made a long series of successive cultures in an inorganic ammoniacal solution, and

* These masses are best seen when the culture is made in an ammonium carbonate solution. If an ammonium chloride or sulphate solution is employed, with solid calcium carbonate, the latter, if not too great in quantity, assumes a curdled appearance as nitrification progresses.

† Dr. P. F. Frankland and myself have each examined more than thirty species.

having thus greatly reduced the number of species present, he proceeded to separate them by the well-known dilution method. After many trials he succeeded in obtaining a nitrified solution which gave no growth on gelatin, and which appeared, when examined microscopically, to contain a single species of bacterium.

Two months afterwards Winogradsky published an account of his isolation of the same organism (*Ann. de l'Institut Pasteur*, 1890, 213). His method was different from that of Frankland. After making a series of cultures in inorganic solutions, till only one species growing on gelatin was present, he collected the gelatinous flocks at the bottom of his culture, washed them, and spread them as thinly as possible upon a surface of nutrient gelatin. After ten days he observed through a lens where growth on gelatin had not taken place. From these places he proceeded to seed ammoniacal solutions, and succeeded, as Frankland had done, in obtaining nitrifying cultures which gave no growth on gelatin.

Later in the same year I also succeeded in obtaining a similar result (*Trans. Chem. Soc.*, 1891, 502). I had been for some time fruitlessly engaged on the subject. The successful result was obtained by the dilution method.

Still later Winogradsky has succeeded in growing the organisms on the surface of gelatinous silica, containing the necessary inorganic food. On this medium ordinary bacteria will not grow, but only those which flourish in inorganic solutions. This method will make future work far easier.

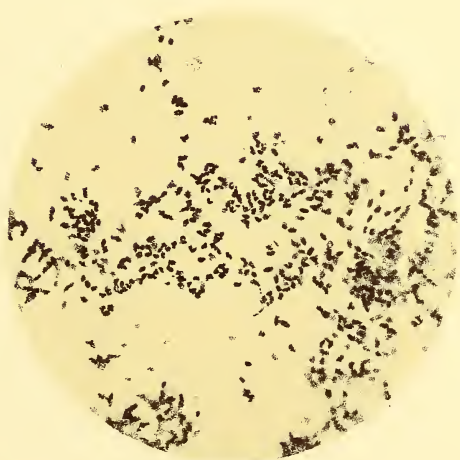
I must now say a word as to the form of the organism. Fortunately your knowledge upon this point will not depend upon the accuracy of my description, as I am able to lay before you some excellent photographs, showing the organism magnified to 1,000 diameters. (Plates VI and VII.)

The organism as found in suspension in a freshly nitrified solution consists largely of nearly spherical corpuscles varying extremely in size. The largest of these corpuscles barely reaches a diameter of $\frac{1}{1000}$ of a millimeter, and some are so minute as to be hardly discernible in the photographs, although shown there with a surface one million times greater than their own. The larger ones are frequently not strictly circular. These forms are universally present in nitrifying cultures. The larger organisms are sometimes seen in the act of dividing.

Besides the form just described, there is another, not universally present in solutions, in which the length is considerably greater than its breadth. In a full-sized organism the length will distinctly exceed $\frac{1}{1000}$ of a millimeter. The shape varies, being occasionally a regular oval, but sometimes largest at one end, and sometimes with the ends truncated. This is the form most generally described as the nitrifying organism. The circular organisms are probably the youngest. The morphology, however, has not yet been fully studied. According to Winogradsky there is a temporary motile stage.



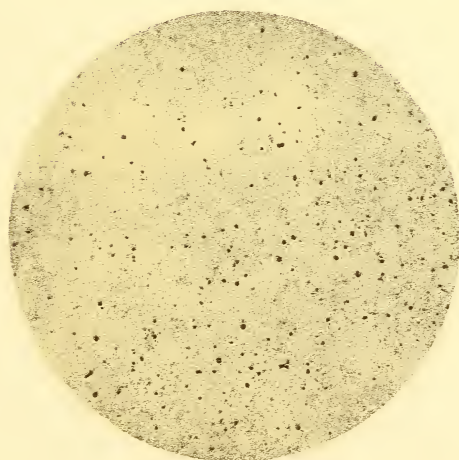
NITROUS ORGANISM IN AMMONIUM CARBONATE SOLUTION.



NITROUS ORGANISM ON SUNK COVER-GLASS IN AMMONIUM CARBONATE SOLUTION.



NITROUS ORGANISM IN 0.5 PER CENT MILK AT 22° C.



NITROUS ORGANISM IN BEEF BROTH AT 22° C.

This organism grows in broth, diluted milk, and other solutions without producing turbidity. When acting on ammonia it produces only nitrites. It is without action on potassium nitrite. It is in fact the nitrous organism which we have previously seen may be separated from soil by successive cultivations in ammonium carbonate solutions.

It is clear that the isolation of this organism has solved only one half of the problem of nitrification. The production of nitrates we will discuss in the next lecture.

LECTURE IV

NITRIFICATION AND DENITRIFICATION.

The separation of the nitric organism—Properties of the nitric organism—Present theory of nitrification—Denitrification—Distribution of the nitrifying organism in soil—Determination of nitrates in soil—Rates of nitrification in soil: (1) Laboratory experiments; (2) results with field soils; (3) the Rothamsted drain gauges.

In the previous lecture I described the separation from soil of an organism having the power of oxidizing ammonia and several other forms of nitrogenous matter to nitrous acid, but which had no power of producing nitrates. Had our knowledge of the subject proceeded no further, it is evident that we should have had no complete theory of nitrification, as the natural process which takes place in soil always results in the formation of nitrates. I am happy to be able to tell you that I have had recently the good fortune to separate an agent having the properties missing in the nitrous organism, an agent, in short, capable of converting nitrites into nitrates (*Trans. Chem. Soc.*, 1891, 484).

THE SEPARATION OF THE NITRIC ORGANISM.

As early as 1881 I was in possession of cultures which were capable of energetically converting nitrites into nitrates, but which appeared to have no power of oxidizing ammonia; the latter fact was so unexpected that I regarded it with some doubt. These cultures were derived from others which had possessed the power of nitrifying ammonia, but the organisms which they contained had since been cultivated in a solution of potassium nitrite. In this fact lay the explanation of the separation effected. It has indeed since been proved that we have only to cultivate the nitrifying organisms of soil in successive solutions of potassium nitrite and the organism which survives will be the one which is able to attack nitrite. At this time, however, I fell into the serious mistake of attributing the power of attacking nitrite to a large bacillus, which slowly formed a dense, white growth upon the surface of my solutions. Every time I removed some of this surface growth to start a new culture of it I removed with it some of the liquid which contained the real nitric agent, and, thus the mistake went on. I was, however, loath to regard this surface growth as the normal nitric agent, as it was clear from a multitude of experiments that the presence of a visible surface growth was by no means essential for the formation of nitrates.

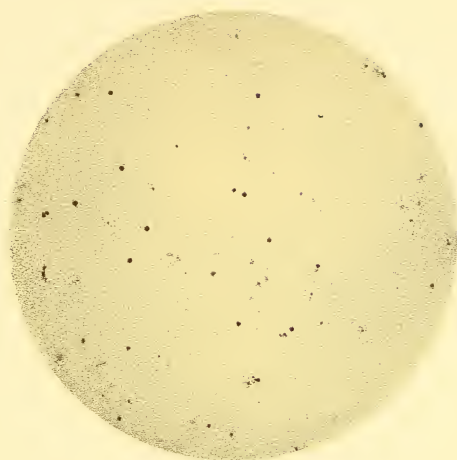


FIG. 1. NITRIC ORGANISM IN POTASSIUM NITRITE SOLUTION.

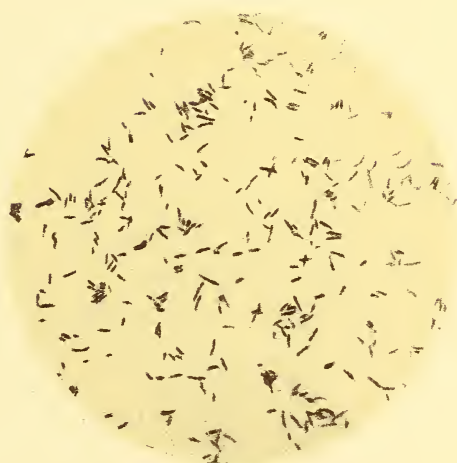


FIG. 2. BACILLUS REDUCING NITRATES TO FREE NITROGEN GAS.

Cultivation upon gelatin and potato, as usual, afforded no help, none of the growths obtained having any power of converting nitrites into nitrates. At last time came to my aid. When in 1890 I returned to the subject, in the almost despairing hope of throwing some light on the formation of nitrates, I found that in several of the original cultures the nitric agent was dead, the power of producing nitrates was lost, but the white surface organism was still alive and grew readily in my solutions. The apparent connection between the surface growth and the production of nitrates was thus severed, and facts no longer required belief in my original but improbable hypothesis. At the same time experiments with a culture in which the power of producing nitrates still remained, showed that by employing a purely inorganic solution containing potassium nitrite and the acid carbonate of sodium, with phosphates, etc., the conversion of nitrites to nitrates would take place speedily and without the development of a surface growth. In this inorganic nitrite solution successive cultures were made.

It has been already stated that the attempts to isolate the nitric organism by cultivation on gelatin or potato failed. I next essayed to isolate it by the dilution method, but in the single series of trials for which I found opportunity I did not succeed in obtaining a culture containing the nitric organism only. In all the solutions seeded with the dilutions to 1,000 and 10,000, the nitrite originally present was converted into nitrate, but in none of those seeded with higher dilutions. Moreover all the successful cultures gave a growth on gelatin, but these growths reintroduced into a nitrite solution were entirely without effect. A few of the successful cultures contained apparently but one species of bacterium growing on gelatin. From these purest cultures stained preparations were made for the microscope. It appeared at once that the bacillus growing on gelatin was present in very small numbers, and it was easy to obtain microscopic fields in which they were absent. Such a field has been photographed, and I am able to show it you to-day. You see at once that we have before us the now familiar features of the nitrous organism, the forms consisting wholly of nearly spherical corpuscles, differing greatly in size, but within the limits previously observed. It would appear, therefore, that in form the nitrous and nitric organism are difficult to distinguish. (Plate VIII, Fig. 1).

Since the publication of my results, Winogradsky has announced the isolation of a nitric organism by culture on gelatinous silica (*Compt. rend.*, 113 (1891), 89). He describes it as a very small bacillus, angular and irregular, and quite distinct in form from the nitrous organism of the same soil. As I did not obtain the nitric organism in a pure state, his statement is of more worth than my own. I may, however, possibly be right, as his organism was obtained from a soil from Quito, and Winogradsky believes that the soils of different countries may contain various forms of the nitrous and nitric organisms.

PROPERTIES OF THE NITRIC ORGANISM.

Little has yet been done to determine the properties of the nitric organism. Like the other nitrifying organism, it develops freely in solutions to which no organic matter has been added. Like it also, its development and action are favored by the presence of the acid carbonates of calcium or sodium. The proportion of the latter should not apparently exceed 6 grams per liter, and a smaller quantity gives a better result. The neutral sodium carbonate is, on the other hand, distinctly prejudicial to the organism. The nutrition of the nitric organism presents no difficulty from the standpoint of the thermochemistry, the energy developed by the oxidation of the nitrite being probably much more than sufficient to leave a balance of heat evolved after the assimilation of carbon from an acid carbonate has been accomplished.

So far the character of the nitric organism appears similar to that of the nitrous; its chemical behavior is, however, widely different.

The nitric organism appears to be without action on ammonia. In no case have I obtained either nitrous or nitric acid in ammoniacal solutions seeded with the purified nitric organism. This certainly is a very strange result, though quite in accordance with my earlier observations. I am happy to say that the fact has been entirely confirmed by Winogradsky.

It appears, further, that the presence of any considerable amount of ammonium carbonate hinders the development of the nitric organism and prevents its action on a nitrite. In a nitrite solution containing ammonium chloride 0.2 gram, with acid sodium carbonate 2 grams per liter, seeding with the nitric organism produced no effect. We have also already seen that cultivation in a solution of ammonium carbonate is the most effectual method for eliminating the nitric organism when in mixture with the nitrous. It is probable, however, that in the case of a mass of soil the addition of ammonium carbonate would have much less influence, partly because the ammonia would be removed from solution by the absorptive action of the soil, and partly by reason of the enormous quantity of the nitric organism present. Schlösing (*Compt. rend.*, 109 (1889), 883) has added large quantities of ammonium carbonate to soil and has successfully nitrified them. He finds, however, that under these conditions nitrous acid is produced and nitrogen lost.

I am unable to tell you whether the nitric organism has any action upon organic matter. The subject is indeed still new and much work remains to be done.

PRESENT THEORY OF NITRIFICATION.

The facts as at present ascertained lead us, then, to believe that the nitrification of ammonia in soil, and probably also the nitrification of other nitrogenous matters, takes place in two stages, each stage being

performed by a distinct organism. By one organism the ammonia is converted into nitrite; by the other the nitrite is converted into nitrate. The existence of these two distinct agents, each of which has special conditions, favorable or unfavorable to its development, explains at once the particular formation of nitrous or nitric acid so frequently observed in laboratory experiments on nitrification.

In soil both organisms are present in enormous numbers, and incubation periods in which no chemical action is manifested consequently do not occur. The action of the two organisms proceeds together, as the conditions are favorable to both. The circumstances which we have seen to be especially unfavorable to the action of the nitric organism are absent. The alkali in the soil is always present as an acid carbonate, and no large amount of ammonium carbonate will occur. If such is added it is removed from solution by the absorptive power of the soil and presently oxidized by the nitrous organism.

If we desire to separate the two organisms in soil we have only to make successive cultivations in solutions of special composition favoring the development of either. If we employ a suitable inorganic solution containing potassium nitrite but no ammonia, we shall presently obtain the nitric organism alone, the nitrous organism feeding on ammonia being excluded. If, on the other hand, we employ an ammonium carbonate solution of sufficient strength, we have selected conditions very unfavorable to the growth of the nitric organism, and a few cultivations leave the nitrous organism alone in possession of the field.

I must not leave this part of the subject without saying a word about the theory quite recently put forward by Müntz (*Compt. rend.*, 112 (1891), 1142). He regards the production of nitrates in soil as brought about by a simple chemical reaction, in which a living organism takes no direct part. Weak solutions of calcium nitrite are, he says, converted into nitrate by the joint action of carbonic acid gas and oxygen. According to his view, therefore, the nitrifying organism of the soil converts ammonia into nitrite, but the further change into nitrate is accomplished by an ordinary chemical operation.

I have not tried the experiments which he describes, but it is quite evident that his theory is insufficient to explain the facts I have laid before you. We have, indeed, seen that the production of nitrite or nitrate in an ammoniacal solution depends on the character of the organisms which we introduce. Moreover, a solution of potassium nitrite containing phosphates, etc., will remain entirely unchanged unless the nitric organism has been added to it. In each series of my experiments there have been unseeded solutions of nitrite, exposed to the same conditions as those seeded, but in no case has the nitrite disappeared. Before commencing the trials respecting the action of carbonic acid I passed a current of this gas for an hour through my potassium nitrite solution, to which Trommsdorf's reagent (zinc iodide and starch) had been previously added; no coloration took place, and it appeared, consequently,

that no nitrous acid had been set free. The statements made by Müntz will doubtless be carefully tested. If proved, they will not affect the facts I have laid before you; they will only show that there is another possible way in which nitrates may be produced in soil.

DENITRIFICATION.

Before turning to the more practical part of our subject and considering the nitrates in agricultural soils and in drainage waters, I must say a little upon the subject of denitrification. So much has been said about the nitrifying power of soil that it may possibly excite surprise to speak of its power of destroying nitrates; under certain circumstances, however, this destruction of nitrates will proceed with vigor, and it is of importance that we should understand the conditions under which this may take place.

Our acquaintance with the phenomena of denitrification belongs to modern times. Dr. Angus Smith in 1867 observed the destruction of nitrates in waters containing sewage, and showed that under these circumstances the nitrogen of the nitrate is evolved as gas. In 1868 Schlösing showed that in a number of putrefactive and fermentive processes nitrates are destroyed and nitrogen or some of its lower oxides produced.

The destruction of nitrates will take place in a moist soil by the simple exclusion of oxygen. Schlösing found that when a moist, humic soil was kept in an atmosphere of nitrogen gas all the nitrates which it contained quickly disappeared. The same denitrifying action took place when only a small and limited quantity of ordinary air was present. If the soil was one rich in organic matter and nitrates had been intentionally added, the process of deoxidation assumed larger proportions, and much carbonic acid and nitrogen were evolved; the nitrogen evolved indeed exceeded that contained in the nitrate originally present, a portion of the nitrogenous organic matter of the soil having been destroyed by the oxygen in the nitrate.

The exclusion of air from a soil may be brought about by saturating it with water. In 1880 I made some experiments in the Rothamsted laboratory on the losses of nitrate which may occur in an ordinary arable soil when the soil is kept saturated with water. The experiment was conducted as follows: A percolator was constructed out of a Winchester quart bottle (holding about 6 pounds of water) from which the bottom had been removed, the bottle being fixed in an upright position, mouth downwards. A disk of copper gauze, covered by a disk of filter paper, was laid inside the neck of the bottle, and upon this 7 pounds of a finely powdered, air dried, arable soil from one of the Rothamsted fields. The column of soil thus obtained was about 8 inches in height and $4\frac{1}{2}$ inches in diameter. Distilled water was poured on the top of the column, and the neck of the percolator was then connected with an ordinary filter pump, to draw away the air contained in the powdered

soil and thus allow the water to descend without disturbing the coherence of the column. Without this precaution it was found that the air escaped upwards through the water, forming channels in the soil. The supply of water to the surface was continued till the soil was saturated and percolation set in. When the drainage water no longer contained nitrates the air pump was disconnected. We then had a column of soil perfectly saturated with water and free from nitrate. Upon the surface of this soil was poured a solution of sodium nitrate equal to a dressing of 519 pounds (80 pounds of nitrogen) per acre. After 1 week had elapsed 120 c. c. of water was placed on the surface of the soil, and when an equal amount of drainage had been collected the application of the water was renewed, the operation being continued until nitrates and nitrites ceased to appear in the drainage water.

Side by side with this experiment there was another column of soil, treated in precisely the same way, save that sodium chloride had been applied in place of sodium nitrate; the quantity of the sodium chloride was the chemical equivalent of the sodium nitrate used in the other experiment. In the experiment with sodium chloride the percolation proceeded regularly, and when 1,320 c. c. of water had been poured on to the surface (120 c. c. per day) and a nearly equal quantity collected as drainage, it was found that the whole of the chloride applied had passed through the soil, and had been recovered in the drainage water. The result where the nitrate had been applied was quite different. In this case large transverse cracks, filled with gas, appeared in the soil, and the water after the first few days passed but slowly. When the drainage water ceased to contain nitrates it was found that only 21 per cent of the nitrate applied had been recovered as nitrate and nitrite in the percolated water; the remainder of the nitrate had suffered reduction. The whole operation had occurred in less than three weeks and at a relatively low temperature (April). The cracks formed were doubtless due to the nitrogen and carbonic acid gas formed within the soil. Some ammonia, as well as nitrite, was found in the drainage water. The experiment was repeated with a similar result. Thus it appears that nitrates are easily reduced in a water-logged soil, even when only a small proportion of organic matter is present.

Müntz has taught us (*Ann. Chim. Phys.*, 11 (1887), 125) that the reducing power of soil is not confined to its action on nitrates, but that under similar circumstances chlorates are reduced to chlorides, bromates to bromides, and iodates to iodides.

We have seen that one condition of denitrification is a deficient supply of oxygen; a condition of still greater importance is the presence of oxidizable organic matter. Indeed denitrification may occur in the presence of oxygen if a sufficient supply of suitable organic matter be present. The influence of organic matter is excellently shown in some experiments by Munro (*Trans. Chem. Soc.*, 1886, 667). He was experimenting with river water possessing active nitrifying powers; a salt

of ammonium added to the water was speedily oxidized to nitrate. When, however, to this water a soluble tartrate was added, all the nitrate present was rapidly destroyed. The power of nitrification is, however, not lost when such destruction of nitrate has taken place; after a time the organic matter disappears from the solution and the process of nitrification again proceeds. There are experiments of my own showing that soil when placed in a solution containing nitrates and sugar exercises an energetic denitrifying action; but I need not enlarge on this point, as every experimenter has fully realized that the presence of oxidizable organic matter is an indispensable requisite for the deoxidation of nitrates. The chemistry of the process indeed consists in the transference of the oxygen of the nitrate to the carbon and hydrogen of the organic matter.

In the process of denitrification we have not, however, to do with an ordinary chemical reaction. A solution containing a nitrate with sugar or a soluble tartrate, undergoes no change if only pure materials are employed. Denitrification, like nitrification, can only occur when the active agent, a living organism, is present. Meusel, in 1875 (*Jour. Pharm.*, (4) 22, 430), was the first to prove that the reduction of nitrates to nitrites in natural waters is brought about by the agency of living organisms, which he pronounced to be bacteria. Dehérain and Maquenne in 1882 (*Compt. rend.*, 95 (1882), 732) were the first to establish the same agency in the case of the reduction of nitrates in soil. It has, in fact, been abundantly shown that if sewage or soil is sterilized by the action of heat or antiseptics no reduction of nitrates will take place.

Many persons have assumed that the action of microorganisms in destroying nitrates was determined simply by the presence of organic matter and the deficiency of oxygen; that in fact the same organisms which produced nitric acid or other highly oxidated products, under the conditions of an abundant supply of oxygen and the absence of much organic matter, would, when the circumstances were reversed, reduce nitrates, chlorates, etc., to a less oxidized state. It is quite true that ordinary soil will either nitrify or denitrify according to the proportion of organic matter and of oxygen present. The action of the river water in Munro's experiment was also clearly determined by the amount of organic matter which it contained. We must, however, bear in mind that both soil and river water contain a multitude of different organisms, and that under varying external conditions different classes of organisms will rise into activity and hold possession of the field, to be in their turn displaced by others when other conditions are established. That this is the right view to take of the varying action exercised by soil and river water becomes more and more evident as our knowledge of the chemical actions of individual species of bacteria is increased.

Gayon and Dupetit (*Compt. rend.*, 95 (1882), 1365), Heraeus (*Zeitsch f. Hygiene*, 1886, 215), Frankland (*Trans. Chem. Soc.*, 1888, 373), and myself (*Ibid.*, 727) have in recent years studied the action of a large

number of microorganisms upon solutions containing a nitrate and organic matter. In my own experiments thirty-seven distinct species of bacteria have been grown in broth containing niter; of these, nineteen energetically reduced the nitrate to nitrite, one of them producing gas; three effected a slight reduction; and fifteen produced no effect. I have taken some of the most vigorous of the non-reducing bacteria, and have grown them in beef broth containing niter, covering the surface of the broth with a layer of paraffin oil. Under these conditions an abundant growth of the organisms was obtained, but notwithstanding the nearly complete exclusion of oxygen and the abundance of organic matter present, no reduction of the nitrate took place. The reduction of a nitrate is thus not determined by simply experimental conditions, however favorable these may be, but depends essentially on the character of the organism present.

The outcome of the action of bacteria upon nitrates is various. The most common form of action is a reduction to nitrite, which afterwards remains unchanged in the solution. Some bacteria possess this power in a high degree, and when grown in broth containing potassium nitrate will rapidly reduce this salt to nitrite. The bacilli of swine fever, of septicæmia, and anthrax, and the micrococci *ureæ* and *prodigiosus*, are powerful reducers of nitrate to nitrite. The well-known hay bacillus, on the other hand, possesses very little reducing power.

Among the reducing bacteria there are a few which carry the reduction of nitrates considerably further and produce nitric oxide, nitrous oxide, or nitrogen gas. The organism which produces nitric oxide gas has not yet been isolated. The fermentation which yields "red fumes" is, however, well known to the manufacturers of beet root sugar; it occurs in the molasses if the solutions are not kept sufficiently acid.

Organisms yielding nitrous oxide gas occur in soil. The production of this gas during the reduction of nitrates by soil was first shown by Dehérain and Maquenne (*Compt. rend.*, 95 (1882), 691, 854). Gayon and Dupetit have since isolated a bacillus from sewage, which, when grown in a solution containing a nitrate and asparagine, produces nitrous oxide gas in such purity that it is capable of reigniting a glowing match brought into it. In the absence of asparagine the same organism produces only nitrogen gas.

As far as I am aware only two or three species of bacteria have been isolated which have been shown to reduce nitrates to nitrogen gas. Two bacilli having this property were isolated by Gayon and Dupetit from sewage (*Ann de la Science Agronomique* 1, (1885), 226) and named by them *Bacterium denitrificans* α and β . I have myself obtained a bacillus from one of my solutions (the source of the bacillus being either soil or atmosphere) which apparently possessed this property, but not to a very high degree. I am able to show you a photograph of this bacillus. (Plate VIII, Fig. 1.) When such organisms are grown in broth containing niter, a froth of gas bubbles appears on the surface of the liquid. Nitrites

are found in the first stage of the reaction, but if the original quantity of niter was not too great the whole of both nitrate and nitrite finally disappears, the liquid becoming highly alkaline, potassium carbonate taking the place of the original potassium nitrate. Gayon and Dupetit's most energetic organism, the *α Bacterium denitrificans*, was capable of reducing 3 grams of niter per day in a liter of chicken broth, and 6 or 9 grams in an artificial solution containing ammonium nitrate and asparagine. Under the latter conditions the liquid evolved in one day its own volume of nitrogen, and its temperature rose 10° C. (18° F.). These facts give us a vivid picture of the energy of the chemical action induced by this organism.

Whether any microorganisms have the power of reducing nitrates to ammonia is at present doubtful. The appearance of ammonia in soil or in broth cultures, in which nitrates have been present, is no proof of its formation from nitrate, as in each case the ammonia may have arisen from the decomposition of nitrogenous organic matter, and this would seem to be in fact the most probable explanation of its appearance.

Ordinary soil contains organisms producing nitrites only, and also those reducing the nitrates to nitrous oxide and nitrogen. When both classes of organisms are present the second class is the one which determines the final outcome of the reaction, the nitrite produced by the first class of bacteria being converted into gas by the bacteria of the second class. Broth containing 10 grams of niter per liter produces an abundance of gas when seeded with soil.

Denitrification is not a process of general occurrence in arable soil. The investigations which have been made show that the air in soil, even at considerable depths, is not very deficient in oxygen. Moreover the subsoils of our fields contain (save in the case of peaty and some alluvial soils) only a very small amount of organic matter, and the presence of this, we have seen, is indispensable for the reduction of nitrates. The reduction of nitrates is to be feared only when the soil has been for some time saturated with water. It will especially occur where much organic matter is naturally present or has been applied to the land as manure.

Denitrification takes place actively in sewage, and in consequence of this fact nitrates are always absent.

DISTRIBUTION OF THE NITRIFYING ORGANISM IN SOIL.

The nitrous organism is one which characteristically belongs to the soil. It is not usually found in the air or in rain water. River water and sewage contain it. It is also generally present in well waters. In the case of deep well waters, however, it is probable that its origin is generally due to the surface soil or to drainage from the surface soil which has found its way into the well, and that it is not a natural inhabitant of the water.

Experiments have been made at Rothamsted respecting the depths to which the organism can be found in the soil; the trials were made in 1883, 1884, 1885, and 1886 (*Trans. Chem. Soc.*, 1884, 645; 1887, 118). At Rothamsted the subsoil is usually clay resting on chalk. In some fields, however, the subsoil is more sandy. Advantage was taken of deep pits which had been sunk for soil sampling, to procure soil at various depths for these experiments. From a clean, fresh surface on the side of the pit a small portion of soil, weighing 0.1 to 0.2 gram, was removed with a platinum spatula, recently heated in a spirit lamp flame. The soil thus removed was immediately introduced into a sterilized solution* contained in a bottle, which was at once closed with its cotton-wool stopper. If nitrification took place in this solution it was concluded that the soil introduced had contained the nitrifying organism; if no nitrification occurred the organism was presumed to be absent.

With soil down to 9 inches below the surface, nitrification was invariable and always occurred with much greater speed and energy than when soil from a greater depth had been employed. In experiments with the subsoil the result depended much on the character of the solution employed. A solution which was readily nitrified by the surface soil might yield no result with a subsoil, which, apparently, in a weaker or less alkaline solution was nevertheless capable of producing nitrification.† The most ready nitrification with subsoil was obtained when gypsum was present in the solution (see p. 50). That the nitrifying organism present in the subsoil was really small in quantity or feeble in condition, was shown by the fact that even with the most favorable solution nitrification was in nearly every case more tardy in commencement than when the surface soil was employed, and this slowness of commencement increased with the increasing depth of the subsoil.

Taking the results when gypsum was present in the solutions and the greatest amount of nitrification was obtained from the subsoils, we find that the nitrous organism was present in almost every trial down to 3 feet below the surface. From this point the number of failures to produce nitrification increased. At 6 feet half the trials made with a clay subsoil were failures. At 8 feet no nitrification was obtained from clay. Six trials were made with the chalk subsoil, which in one of the pits was only 5 feet from the surface; in no case did the chalk produce nitrification. At the date of these experiments the distinction between nitrous and nitric organisms was unknown. That the nitrous organism was present in every case in which nitrification occurred is certain, as nitrous acid was always found. In one series of trials the observation of the solutions was continued till the conversion of nitrites into nitrates; this certainly occurred with soil from all depths down to 4 feet below the surface.

* The solution consisted of 4 c. c. of urine in 1 liter of water, some calcium carbonate and in the later experiments some gypsum being also present.

† This is the best explanation I can give of the varying results obtained; the explanation is a probable one, but is not wholly proved.

There can be no doubt that nearly the whole of the nitrification which occurs in the heavy land at Rothamsted takes place in the surface soil; of this fact we shall have several illustrations by and by. With a sandy soil nitrification will probably be active at a greater depth.

The conditions which would favor nitrification in the subsoil are those which would enable air to penetrate it, as artificial drainage or the growth of a luxuriant crop causing much evaporation of the water of the soil. Such conditions, by removing the water which fills the pores of the subsoil, will cause air to penetrate more or less deeply and render nitrification possible. Subsoil nitrification will thus be most active in the drier periods of the year.

The facts relating to the distribution of the nitrifying organisms in the soil should be borne in mind when arranging for the purification of sewage by intermittent filtration. Little will clearly be gained by making the filter bed of considerable depth when we are dealing with a heavy soil in its natural state of consolidation. If an artificial bed is to be constructed a surface soil rich in nitrifying organisms should be exclusively made use of.

We must not leave this section of our subject without mentioning that Müntz has found that the disintegrating surfaces of rocks in the Alps possess the power of starting nitrifications in appropriate solutions. He believes the nitrifying organism to be an active agent in effecting the disintegration of rocks.

DETERMINATION OF NITRATES IN SOIL.

Before speaking of the quantity of nitrate found in various Rothamsted soils, it will be well to say a word upon the method of analysis which has been followed.

The general plan of sampling soil employed at Rothamsted has been already described. It is imperative if nitrates are to be determined that the soil be dried immediately after the sample has been taken; if this is not done nitrification will proceed in the soil and the results found will be considerably above the truth. The drying must however be done at a low temperature. A wet soil dried in a water oven at 100° C. may lose a considerable amount of nitrate. The temperature I should recommend would be 55° C.; this would be sufficient to stop the progress of nitrification.

The soil having been reduced to an air-dry condition and finely powdered, the next step is to extract the nitrates present. This is done best by means of a filter pump. A wide, shallow funnel, made by cutting off the top of a Winchester quart bottle, answers best. In this is laid a disk of copper gauze which is covered by two disks of filter paper, the upper one a little larger than the under. When the filter has been moistened, 100 to 400 grams of the dry, powdered soil is introduced and shaken down. Water is then applied till the soil is saturated. Connection is now made with the pump and fresh additions of water placed on the

surface of the soil as the water disappears, care being taken to close any cracks that may arise by pressing the soil with a glass rod. If the operation has been carefully performed it will be found that the whole of the nitrates and chlorides in the soil has been extracted when 100 c. c. of filtrate have been obtained.

The ease with which the soluble salts are removed from a dry, powdered soil by the steady downward passage of a column of water, is remarkable. In an experiment made with 7 pounds of soil, forming a column 8 inches deep, more than three quarters of the nitrates and chlorides present were found in the first 50 c. c. of filtrate obtained. The column of water passing through the soil evidently dissolves the soluble salts at its lower edge and pushes this solution before it as a narrow layer, which is finally expelled as filtrate.

The watery extract of a dried soil is often faintly acid; a small excess of limewater is therefore added to the filtrate before evaporating it to a small bulk. The method which I have found by far the best for the determination of nitric acid in soil extracts and in all other cases where much organic matter is present, is that of Schlösing, which I employ with some modifications, the details of which will be found in *Trans. Chem. Soc.*, 1880, 468; 1882, 345, 351. The principle of the method lies in the conversion of the nitrate into nitric-oxide gas by boiling with ferrous chloride and hydrochloric acid. For the reaction to be complete it is necessary to boil to dryness. For this reason it is advisable to heat the small retort in which the operation is conducted, in a bath of calcium chloride kept at 130° to 140°. It is also necessary for accurate results that oxygen be entirely excluded from the apparatus. This is accomplished by the previous expulsion of air by a stream of carbonic acid, which is again used at the end of the operation to drive out the last portions of nitric oxide. If the chemist has an apparatus for gas analysis, the nitric oxide is most simply and accurately determined by measurement. The carbonic acid is absorbed by potash and the gas measured. The nitric oxide is then removed by successive treatment with oxygen and pyrogallol, and the residual gas again measured. The difference between the two measurements gives the nitric oxide. Those chemists who have not a gas-analysis apparatus may employ Schlösing's original process, in which the nitric oxide is converted into nitric acid and titrated with standard alkali.

Schlösing's process can not be conveniently used when nitrites are present. In such cases it is best to convert the nitrites into nitrates by means of potassium permanganate before proceeding to the determination.

RATES OF NITRIFICATION IN SOIL.

(1) *Laboratory experiments.*—The quantity of nitrate which may be formed in soil under favorable circumstances is very large and the progress of nitrification very rapid. The most striking instance I am aware of is furnished by one of Schlösing's experiments, in which

ammonium sulphate had been mixed with a soil rather rich in organic matter and containing 19 per cent of water. During the twelve days of active nitrification, nitrogen was oxidized at the rate of 56 parts per million of dry soil per day. To enable you to obtain a practical idea of what this rate of nitrification implies, I may remind you that the surface soil on an acre, about 4 inches deep, will weigh about 1,000,000 pounds. We have thus a daily oxidation in soil 4 inches deep at the rate of 56 pounds of nitrogen per acre, equivalent to the production of 340 pounds of sodium nitrate.

The greatest rate of nitrification I have noticed when working with ordinary arable soil (first 9 inches) from the Rothamsted farm, has been about 70 parts of nitrogen per million of air-dried soil in one hundred and nineteen days (0.588 per day). Similar soil supplied with ammonium chloride nitrified about 110 parts per million in the same time (0.924 per day). In each case the powdered soil was loosely placed in a percolator and was nearly saturated with water at starting (water equaling 28 per cent), but afterwards remained untouched during the one hundred and nineteen days.

Lawes and Gilbert (*Trans. Chem. Soc.*, 1885, 415) working with the far richer Manitoba soils, and with a higher temperature, obtained in two cases (soils from Selkirk and Winnipeg) average daily rates of nitrification of 0.7 part of nitrogen per million during three hundred and thirty-five days, the rates during the earlier portion of this period being as high as 1.03, 1.24, 1.36, and 1.72 per million. The greatest proportion of nitrogen nitrified in three hundred and thirty-five days was 5.4 per cent of that originally present in the soil.

Dehérain (*Ann. Agron.*, 1887, 245; 1888, 292) working with a soil containing 0.16 per cent of nitrogen, obtained daily rates of nitrification varying from 0.71 to 1.09 per million in ninety days. In the most successful experiment about 6 per cent of the nitrogen of the soil was nitrified in one hundred days. Working with a richly manured soil containing 0.261 per cent of nitrogen, he obtained a maximum daily rate of nitrification during forty days of 1.48 of nitrogen per million of soil. When the soil was exposed to alternate drying and watering, the daily rate of nitrification was increased to 1.8 per million during one hundred and four days. During the first month the rate was 2.4 per million.

It has been generally noticed in experiments of this kind that the rate of nitrification in a soil rapidly diminishes as the trial proceeds, the easily nitrifiable matter being first oxidized and the subsequent action proceeding, in consequence, more slowly. The rate of nitrification increases somewhat with the proportion of water present, provided that the moist soil still remains porous; beyond this point denitrification sets in. Boussingault observed that soils with 60 per cent of water lost the greater part of their nitrates in a few weeks. Dehérain obtained his most active nitrification by periodical watering,

the soil being allowed to partially dry between the applications of water. He found that finely powdering the soil had a great influence in increasing the rate of nitrification.

The nitrogenous organic matter of the subsoil is apparently not so easily nitrified as that occurring in the surface soil when placed under similar conditions, but the relation between the two requires further investigation.

(2) *Field results.*—The best examples of the amount of nitrates produced under favorable conditions in field soils are furnished by the analysis of soils that have been lying in bare fallow. The ancient practice of leaving the land for one whole season without a crop, during which time it is repeatedly plowed, is still followed to some extent upon heavy land in England. Bare fallow forms a part of more than one of the experimental rotations at Rothamsted, and has also been occasionally employed on the farm for the purpose of cleaning the land; opportunity has thus been afforded for ascertaining the quantity of nitrate present in the soil after a season which has passed without manure and without a crop. The results obtained in analyses of various fallow soils will be found in Table VII.

The soils were all sampled in September or October, at the end of the fallow season.

TABLE VII.—*Nitrogen as nitrates in Rothamsted soils after bare fallow, in pounds per acre.*

Depth of soil.	Alternate wheat and fallow.	Four-course rotation.		Claycroft field.	Foster's field.
		Superphos- phate only.	Mixed manure.		
		1878.	1878. 1882.		
	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>
First 9 inches.....	28.5	22.3	30.0	40.1	16.4
Second 9 inches.....	5.2	14.0	18.8	14.3	26.5
Third 9 inches.....				5.5	15.9
Total	33.7	36.3	48.8	59.9	58.8
					56.5

The alternate wheat and fallow land had been cropped in this manner since 1851 (twenty-seven years), and had during the whole of this time received no manure. The four-course rotation was the usual one of turnips, barley, beans, or clover and wheat. In one division of the rotation field a bare fallow takes the place of the leguminous crop. One part of the field receives a complete artificial manuring for the turnips; in another part the turnips received a mineral superphosphate only; this mode of treatment dates from 1848. Claycroft and Foster's were two fields under ordinary farm culture.

In each case, save that of the alternate wheat and fallow, the crop preceding the bare fallow had been barley, and we may safely assume that at the time of the barley or wheat harvest these soils contained in the 27 inches now under consideration only very small quantities of

nitric acid.* The nitrates present after the season of bare fallow are thus practically the produce of the nitrification which has taken place during fallow.

The position of the nitrates in the soil depends on the character of the season. The nitrates are produced almost exclusively in the surface layer of soil, the layer richest in nitrogenous matter and the only part broken up by the plow. But if heavy rain occurs after the formation of the nitrates they will be washed out of the surface soil and may be found to a large extent in the subsoil. The examples given in Table VII show that at the end of the summer of 1878 and 1882 the nitrates were found chiefly in the first 9 inches of the soil, though considerable quantities occurred in the second 9 inches and doubtless some in the third. In the season of 1881, on the other hand, the nitrates were found chiefly in the second 9 inches, and the third 9 inches actually contained as much as the first.

Owing to this washing down of the nitrates to lower levels, the analyses given in Table VII do not in any case exhibit the whole amount of nitrate produced. The quantities found in 1882 and in the alternate wheat and fallow of 1878 appear to most nearly represent the truth, while the results obtained in 1881 must be very decidedly too low. The measurements of the amount of drainage through the soil, furnished by the Rothamsted drain gauges, and the analyses of the drainage waters from Broadbalk wheat field and from the uncropped and unmanured soil of the drain gauges, enable us to estimate pretty nearly the amount of nitrate which passed below 27 inches during the whole season of fallow. Adding this amount to the quantities found in the soil, we arrive at 86.5 pounds of nitrogen per acre as the quantity nitrified during the season of 1881-82, and 89.5 pounds as the amount nitrified in 1880-81. These quantities are equal to 553 pounds and 572 pounds, respectively, of ordinary sodium nitrate per acre.† We must recollect, however, that these amounts of nitrate represent the nitrification of fourteen or fifteen months and not of a single year. The amounts just mentioned, though large, are of course less than would be yielded by rich or well-manured soils, and are much less than those already quoted as obtained in laboratory experiments.

Before passing to other results a word must be said as to the light which these facts throw upon the practice of fallow. A farmer employs a fallow because of the facilities it offers for removing weeds and the greatly improved mechanical condition of the soil which results from the frequent tillage; but we now see that there is at the same time another result at least equally important, namely, the production of a large quantity of nitrates. If a farmer could insure dry seasons, so that the nitrates produced during a bare fallow should remain in the soil avail-

* Illustrations of the very complete removal of nitrates from the soil by wheat and barley will be given later on.

† One pound of nitrogen is contained in about 6.4 pounds of ordinary sodium nitrate.

able for the succeeding crop, it would pay him better to have an alternation of wheat and bare fallow rather than to grow wheat continuously, as on the former plan he would spend less upon seed and labor, while obtaining in the long run at least an equal produce.

In the English climate no such favorable result can be expected. An experiment has been made at Rothamsted on the growth of wheat alternating with fallow, the experiment being so arranged that there is each year a crop of wheat succeeding a bare fallow. We can thus compare the results obtained by this mode of culture with that yielded by wheat grown continuously on the same farm. Dividing the thirty years (1856-85) into two equal periods, we find that the total product of wheat after fallow was to wheat after wheat as 150: 100 during the first fifteen years and as 129: 100 in the second fifteen years. The wheat after fallow, except in some of the earliest years, has thus not given the double produce which should result from the presence of a double supply of nitrates. It is also further evident that the fallowed land has declined in fertility more quickly than the land which has been continuously cropped. The soil analyses already quoted (Lecture II, Table V) show, indeed, that the nitrogen of the soil has fallen off most in those cases in which spring and summer tillage has been employed.

(3) *Rothamsted drain gauges*.—I must now call your attention to the results which have been obtained from the soils of the Rothamsted drain gauges. The drain gauges are three in number. The blocks of soil forming these drain gauges have each an area of $\frac{1}{1000}$ of an acre and have a depth of 20, 40, and 60 inches, respectively. The gauges were constructed in 1870, in a field which had been under ordinary arable culture. A deep trench was dug in the first place along the front of the block of soil to be isolated. It was then undermined and supported by perforated cast iron plates. These were afterwards strengthened by transverse iron girders, and the ends of the plates and girders supported by brickwork on three sides. The soil being thus supported, trenches were opened at the sides, and the blocks of soil were inclosed by $4\frac{1}{2}$ -inch walls of brick laid in cement. The walls were carried 3 inches above the level of the soil, the edges at the top being made to slope outwards. The side trenches were then filled in with earth. Below the perforated iron plates is fixed a large zinc funnel. The drainage water is collected by this funnel and is delivered into a series of cylinders having graduated gauge tubes. In these the water is measured and from these samples can be taken.

Analyses of the daily runnings from the drain gauges have been made in some instances, but the systematic work has consisted in the analyses of mixed samples, each representing a month's drainage. Every day in which drainage occurs a fixed proportion of the drainage is placed in a carboy, 1 gallon being taken for every inch of drainage. By following this plan the carboy will contain at the end of the month

a fair sample of the month's drainage. This proportional method of sampling is essential if accurate results are desired, as the composition of the water may vary greatly on different days.

The nitric acid contained in the drainage waters is determined by the improved indigo method (*Trans. Chem. Soc.*, 1879, 578), which admits of a determination being made in about half an hour.

It is unfortunate that we do not know the quantity of nitrates which pass from the drain gauge soils during the first seven years after their isolation, the proportional sampling of the drainage waters commencing in May, 1877. Of the previous period we possess only analyses of individual samples and of mixtures imperfectly prepared and preserved. This fact throws considerable difficulty in the way of any conclusion as to the rate of decline in the production of nitric acid in the soil. There can be no doubt, however, that the rate of production has diminished. The decline was probably at first rapid and is now proceeding slowly.

The annual discharge of nitrates from the soil has naturally varied very much, the chief determining factor being the extent to which the soil has been washed out by rain. Reckoning the year from April to March, for a reason which will be made plain in our next lecture, the largest quantity of nitrate discharged from the soil 20 inches deep in one year, has been equivalent to 54.2 pounds of nitrogen per acre, contained in 21.66 inches of drainage water in 1880-81, while the smallest quantity has been 20.9 pounds discharged during the year just expired (1890-91) in 8.96 inches of drainage. The average quantity of nitrogen as nitrate discharged from the soils during thirteen years has been for the 20-inch gauge 37.3 pounds, for the 40-inch gauge 32.6 pounds, and for the 60-inch gauge 35.6 pounds per acre, equivalent respectively to 239, 209, and 228 pounds of ordinary sodium nitrate. This then is the amount annually produced in land left for many years unmanured, lying in its natural state of consolidation, and receiving no aëration from tillage. All vegetation that appears on these soils is removed.

The quantity of nitrates produced in a soil depends, of course, largely upon the richness of the soil in nitrogenous matter. When the gauges were constructed in 1870 the soil was sampled and analyzed. The first 9 inches contained 0.146 per cent of nitrogen in the dry soil, the second 9 inches 0.078 per cent. The soil, like that of the other Rothamsted fields, contains much clay and many flints.

From a practical point of view the facts taught by the drain gauges are sufficiently startling. That a poor, arable soil, without vegetation, should lose annually by drainage-nitrates equivalent to 2 cwt. per acre of sodium nitrate, is a fact which touches a farmer's pocket. Such a quantity of nitrate has a considerable money value, and when it has once passed into the subsoil drainage water it is removed without producing any profitable results. The conditions which prevent or diminish such losses will be pointed out in following lectures.

LECTURE V.

NITRIFICATION OF SOILS AND MANURES.

Production of nitrates in uncropped soils throughout the year—Nitrates in cropped soils—Use of crops to prevent loss of nitrates—Nitrates in soils cropped and manured—Nitrification of manures.

PRODUCTION OF NITRATES IN UNCROPPED SOILS THROUGHOUT THE YEAR.

I must call your attention once more to the facts shown by the Rothamsted drain gauges. In Table VIII you will find the average monthly results obtained from the shallowest and deepest soils during thirteen years (1877–90), with the rainfall during the same period.

You will see that the average rainfall has been about 30 inches. The rain is at its minimum in March and then steadily rises till July. The months of August and September are a little drier. The maximum rainfall is reached in October and November, after which there is a considerable decrease in the amount.

The average annual drainage through bare, uncropped soil during the thirteen years has been about 15 inches, or one half the rainfall. The drainage, however, bears no fixed proportion to the rainfall; the drainage in any year is in fact merely the excess of rainfall over evaporation, and the quantity of water annually evaporated from a bare soil is a fairly constant quantity.

TABLE VIII.—*Amount of drainage and nitrogen as nitrates in drainage water from unmanured bare soil, 20 and 60 inches deep—average of thirteen years.*

	Rainfall.	Amount of drainage.		Nitrogen as nitrates.			
				Per million of water.		Per acre.	
		20-inch gauge.	60-inch gauge.	20-inch gauge.	60-inch gauge.	20-inch gauge.	60-inch gauge.
	<i>Inches.</i>	<i>Inches.</i>	<i>Inches.</i>			<i>Pounds.</i>	<i>Pounds.</i>
March.....	1.70	0.85	0.94	7.3	8.9	1.41	1.89
April.....	2.25	0.72	0.79	8.3	9.0	1.35	1.61
May.....	2.48	0.80	0.79	8.4	9.1	1.53	1.63
June.....	2.59	0.78	0.78	9.2	9.1	1.62	1.60
July.....	2.85	0.68	0.62	13.5	11.8	2.08	1.66
August.....	2.69	0.84	0.76	15.1	13.3	2.87	2.28
September.....	2.70	0.97	0.82	17.7	13.4	3.86	2.50
October.....	3.12	1.86	1.68	13.8	11.9	5.83	4.53
November.....	3.20	2.44	2.32	11.8	11.4	6.50	5.98
December.....	2.34	1.88	1.88	9.5	10.6	4.06	4.51
January.....	2.13	1.79	1.93	7.4	8.9	2.99	3.88
February.....	2.16	1.84	1.74	7.7	9.1	3.19	3.57
March-June.....	9.02	3.15	3.30	8.3	9.0	5.91	6.73
July-September.....	8.24	2.49	2.20	15.6	13.0	8.81	6.44
October-February.....	12.95	9.81	9.55	10.2	10.4	22.57	22.47
Whole year.....	30.21	15.45	15.05	10.7	10.5	37.29	35.64

The drainage from 60 inches of soil is seen to be on an average only 0.4 inch less than that from a soil 20 inches deep; the evaporation is thus only slightly greater from the deeper soil. The amount of drainage varies much at different periods of the year. Evaporation is greatest in July; in this month 100 parts of rain give on an average about 24 parts of drainage. It is least in December, when 100 parts of rain yield 80 parts of drainage. The principal amount of drainage occurs in five months of the year, October to February; during these five months 63 per cent of the total drainage of the year takes place.

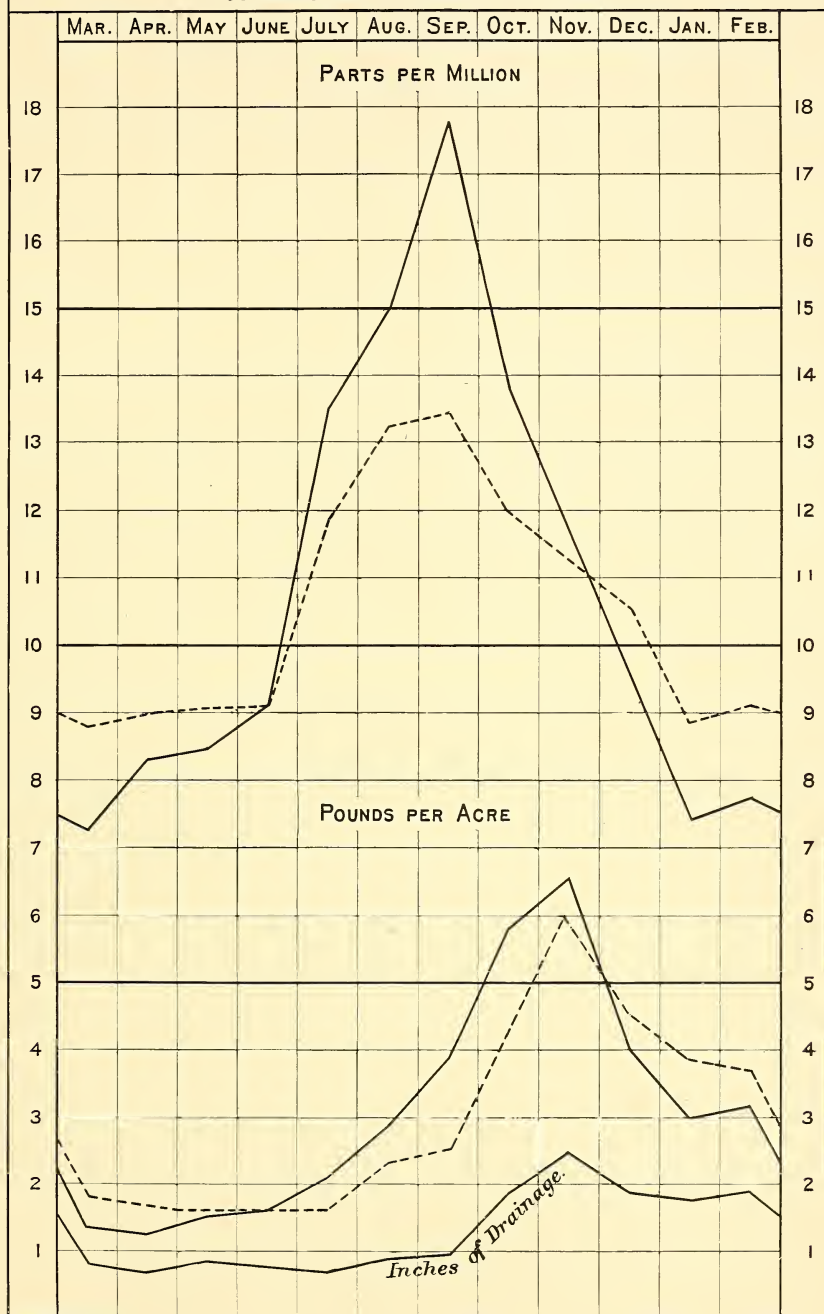
The proportion of nitrates in the drainage water varies greatly at different periods of the year.* The minimum proportion occurs, on an average, in March. The soil has then been washed out by the winter rains and the temperature has not yet sufficiently risen for active nitrification to recommence. In April and May there is a slight rise in the proportion of nitrates. In June the rise becomes very distinct in the drainage from the shallowest soil. In July a great leap upwards is taken. The maximum for the year generally occurs in September, after which the strength of the drainage water diminishes. The changes in the strength of the drainage at different seasons of the year are shown most strikingly in the case of the drainage from the shallowest soil. The drainage from 60 inches of soil is much more uniform in strength throughout the year, the proportion of nitrates neither falling so low nor rising so high as in the drainage from the 20-inch gauge, a result which naturally follows from the greater mass of the soil and the larger quantity of nitrates which it contains. At a more considerable depth the drainage water must have a uniform composition throughout the year.

When we turn to the quantity of nitrogen as nitrates removed in the drainage water we see that the minimum discharge occurs in April, in fact at about the time that the drainage has reached its minimum strength. The greatest discharge does not, however, occur at the season when the water is strongest, but as late as November, when the quantity of water passing through the soil is most considerable. In the five months from October to February, more than 22 pounds of nitrogen as nitrates per acre have been on an average discharged from the soils 20 and 60 inches deep, being respectively 60.5 and 63 per cent of the whole annual discharge. The principal discharge from the deeper soil occurs somewhat later than that from the shallower soil.

* The average proportion of nitrogen as nitrates per million of water given in the table is not the mean result of thirteen analyses, but represents the average strength of the water in thirteen years, calculated from the average quantity of drainage and the average weight of nitrogen as nitrates which it contained. The former method of calculating would be inaccurate.

AMOUNT OF DRAINAGE AND NITROGEN

AS NITRATES IN DRAINAGE WATER FROM AN UNMANURED BARE SOIL, 20 AND 60 INCHES DEEP—AVERAGE OF 13 YEARS



The months mentioned as those of maximum and minimum discharge are those which would exhibit this character in an average of many seasons, but it frequently happens otherwise. The first month after the middle of summer in which a large drainage takes place is generally the month of maximum discharge of nitrates; the first large drainage may, however, occur in any month from August to February. In consequence of this irregularity of the seasons it is necessary in work of this kind to repeat the experiment for many years before a truly average result can be obtained. The present average of thirteen years which I bring before you is still imperfect; the results for February are conspicuously too high.

In Plate IX the results yielded by the 20-inch and 60-inch drain gauges are exhibited in a graphic form. The lowest line shows the average amount of drainage in inches for each month in the year; the two lines next above show the quantity of nitrogen as nitrates in pounds per acre discharged in the drainage waters. The upper two lines represent the strength of the drainage waters—the amount of nitrogen as nitrate in parts per million. In each case the dotted line shows the result furnished by the 60-inch gauge.

You have seen that the most considerable loss of nitrates occurs during the winter months. There can be no doubt that in countries where the soil remains frozen during the winter this loss will be considerably diminished. In such countries the snow accumulated on the soil during the winter months will thaw in springtime before the soil becomes permeable, and the resulting water will pass off by surface drainage without penetrating the soil.

NITRATES IN CROPPED SOILS.

Turning next to the quantity of nitrates contained in soils bearing a crop, I will invite you in the first place to consider the facts shown by the drainage waters from the unmanured plot in Broadbalk wheat field. In this field a drainpipe passes down the middle of each of the principal plots at a depth of about 2.5 feet from the surface. The ends of the drainpipes are free, and samples of the water are collected every day in which drainage occurs. The quantity of water passing through the soil of each plot is however unknown; accurate quantitative results are thus unattainable, but much valuable information is furnished respecting the influence of the crop and of the season of the year upon the composition of the drainage waters, and especially concerning the losses which follow the application of manures. We will confine ourselves at present to the simplest case in which the disturbing effect of manure does not occur.

The record kept of the number of runnings of the drainpipes furnishes information as to the relative amount of percolation at different seasons of the year. With the greater amount of evaporation from the surface caused by the presence of the wheat crop, the spring and

summer drainage are greatly diminished. Thus 75 per cent of the runnings of the drainpipe from the unmanured plots 3 and 4 has occurred in the five months from October to February, and on plot 7, where a larger crop has been grown, 80 per cent of the runnings has occurred during this period on an average of twenty years. Summer drainage indeed only occurs when the rainfall is unusually heavy and continuous. In consequence of the more complete drying of the soil during the summer months, the season of free drainage commences later in the autumn than is the case with the uncropped soils of the drain gauges.

In Table IX you will find the average proportion of nitrogen as nitrates and of chlorine found in the drainage water from the unmanured wheat plot during twelve years. The average composition of the water in each month is given so as to exhibit the effect of season.

TABLE IX.—*Nitrogen as nitrates and chlorine in the drainage water from unmanured wheat land, 1878-90.*

	Runnings of drain- pipe in 12 years.	Per million of water.		Nitrogen to 100 chlorine.
		Nitrogen as nitrates.	Chlorine.	
	<i>Days.</i>			
March	17	2.0	5.3 }	39.7
April	11	1.9	4.5 }	
May	8	0.9	3.3 }	16.1
June	8	0.1	2.9 }	
July	8	0.1	2.3 }	5.0
August	9	0.1	2.3 }	
September	5	3.9	9.0 }	49.6
October	23	4.6	9.1 }	
November	32	3.6	7.4 }	58.9
December	30	4.8	6.9 }	
January	24	3.1	5.2 }	63.6
February	37	4.0	6.1 }	
March-May	36	1.7	4.6	37.6
June-August	25	0.1	2.5	4.4
September-November	60	4.0	8.2	49.4
December-February	91	4.0	6.1	65.9
Average		3.2	6.0	52.9

You will recollect that in the drainage from the uncropped soils of the drain gauges (Table VIII) the proportion of nitrates began to increase after March and in August it had nearly reached the maximum strength of the year. When, however, the soil is covered by a wheat crop the proportion of nitrates in the drainage water rapidly diminishes as soon as spring commences and the crop begins to grow. When the spring is a forward one, as in 1884, the nitrates may disappear from the drainage of the unmanured wheat plot in March; in other years the disappearance has occurred in April or May. In June it is rare to find nitrates in this drainage water. Out of the twenty-five samples of drainage collected in June, July, and August during twelve years, only three contained any nitric acid. We may thus fairly conclude that at this time of the year the 2.5 feet of soil above the drainpipe is practically

free from nitrates. In September, the crop being now removed, nitrates are always found in the drainage water. In a wet season the maximum amount of nitrates will occur in October. The proportion of nitrates will be maintained with little diminution during the winter months and begin to fall again in March.

The proportion borne by the nitrates to the chlorides at different times of the year is very instructive. The greater assimilation of nitric acid than of chlorine by the crop occasions a great diminution in the relative amount of nitrates during the summer months, while the steady production of nitrates in the soil during the winter months is shown by the gradual increase in the proportion of nitrates to chlorides during this season.

The facts I have just brought before you not only illustrate the effect of a growing crop in removing nitrates from the soil, but they also point out the great defect of cereal crops, considered as conservers of soil nitrogen. The active growth of cereal crops ceases generally in July and they are entirely removed from the land in August or September; they are thus unable to afford protection against loss of nitrates during the autumn months, the season at which the greatest losses occur. From this point of view maize is a more economical crop than either wheat, oats, or barley, its growing period extending through the whole of the summer. Nor must we forget that the need which a crop has for nitrogenous manure is in inverse proportion to its own power of assimilating nitrogen. After a wet winter cereal crops begin to grow in a soil impoverished of its nitrates, and the growth of most cereal crops is over before the summer production of nitrates is half accomplished. Cereal crops are thus especially benefited by nitrogenous manures, and particularly by the application of nitrates, while, for the reason already given, maize is more independent of such manuring than wheat or barley. The beneficial influence of a dry winter upon the crops of the ensuing year is now generally recognized.

I have called your attention in the first instance to the results exhibited by the drainage water of unmanured wheat land, because these results enable us to trace the rise and fall of the nitrates in the soil at different seasons of the year. I will now lay before you (Table X) actual determinations of nitrogen as nitrates in the soil and subsoil of land which had lately grown or was still growing a crop at the time of sampling. The instances I shall give refer to land to which no nitrogenous manure had been for many years applied. The crops were, however, of quite average luxuriance. The wheat soil in the Agdell rotation experiments was sampled late in the year; the soils carrying leguminous crops were sampled in July after hay had been made.

TABLE X.--Nitrogen as nitrates in cropped soils receiving no nitrogenous manure, in pounds per acre.

Depth.	Wheat.		Bokhara clover, 1882.	Vetches, 1883.	Lucern, 1885.	White clover, 1885.
	After fallow, 1883.	After clover, 1883.				
	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>
First 9 inches.....	3.4	6.1	3.4	10.2	8.9	11.5
Second 9 inches.....	2.1	4.4	1.0	2.7	1.1	1.4
Third 9 inches.....	0.8	1.6	0.6	1.1	0.8	0.9
Fourth 9 inches.....	1.0	1.3	1.0	1.5	0.8	1.9
Fifth 9 inches.....	0.8	1.5	0.8	2.5	1.0	7.1
Sixth 9 inches.....	0.6	0.8	1.7	4.4	0.9	11.3
Seventh 9 inches.....	0.8	2.2	-----	4.5	0.6	13.1
Eighth 9 inches.....	0.9	1.7	-----	4.9	0.8	12.6
Ninth 9 inches.....	0.7	2.4	-----	4.8	0.7	11.2
Tenth 9 inches.....	2.0	2.1	-----	5.1	0.6	10.7
Eleventh 9 inches.....	1.5	2.1	-----	6.4	0.4	11.1
Twelfth 9 inches.....	3.8	2.8	-----	6.5	0.4	10.0

The leguminous crops were those grown continuously in Hoos field. The Bokhara clover (*Melilotus leucantha*) was the fifth successive crop on the same land, vetches (*Vicia sativa*) the sixth, lucern (*Medicago sativa*) the sixth, and white clover (*Trifolium repens*) the seventh, including, however, several years in which there was practically no crop. All these leguminous crops received manures supplying ash constituents, but no nitrogen had been applied to the land since 1849.

On glancing at the figures in Table X, we see at once that the quantity of nitrogen as nitrates present in these soils is quite small when compared with that found in a soil after a season of bare fallow, in which nitrification has proceeded in the absence of a growing crop. Instead of 40 to 60 pounds of nitrogen as nitrates occurring in the first 27 inches of the soil, we have in this depth only 5 to 14 pounds, and this nitrate is mostly present in the first 9 inches. As active nitrification is always in progress at the surface it requires a very energetic and continuous assimilation of nitrates by the crop to reduce the nitrates in this layer to an insignificant amount.

Below the surface soil we find a very considerable depth in which nitrates are practically absent, the amount of nitrogen as nitrates in 9 inches of subsoil being frequently less than 1 pound per acre. The depth to which this nitrate-free layer of subsoil extends apparently varies according to the range of the roots of the crop. It is least in the case of the land growing white clover, distinctly greater where vetches were cultivated, still greater in the case of wheat, and greater still in the case of lucern, the subsoil being here fully exhausted of nitrates at a depth of 9 feet from the surface. An old, well-established plant of lucern, like that which was the subject of experiment in the present case, has indeed a more widely extended system of roots than any other crop grown at Rothamsted; its roots have been traced to a depth of 9 feet from the surface. To this extended system of roots the crop doubtless owes its remarkable indifference to drouth.

Below the nitrate-free layer of subsoil comes a layer in which a notable, and in the case of one of the subsoils represented in the table, a very considerable amount of nitrate exists. What is the meaning of this?

The proportion of nitrates in the deeper layers of the subsoil is determined by the average strength of the drainage water passing through the soil and by the amount of water that the subsoil retains. Thus the average strength of the drainage water passing through the soils of the drain gauges is shown by Table VIII to be 10.5 or 10.7 of nitrogen as nitrates per million of water. Nine inches of a clay subsoil, if saturated, would contain about $1\frac{1}{2}$ million pounds of water, and if saturated with drain gauge water would hold about 16 pounds of nitric nitrogen per acre. There can be little doubt that in the case of the deepest drain gauge this is about the proportion of nitrates present in the subsoil. Let us turn to another case, less accurately known—that of the drainage from the unmanured wheat plot in Broadbalk field mentioned in Table IX. We have here an average composition of the runnings from the drainpipes of 3.2 of nitrogen as nitrates per million of water. The saturated subsoil of this plot, beyond the range of the roots, should thus contain in each 9 inches about 4.8 pounds of nitric nitrogen per acre. Of course when the subsoil is not saturated with water it will contain less. Of course, also, this regular content of nitrate is confined to subsoil of such a depth as to be unaffected by the variations due to crop and season. Above this depth the proportion of nitrate present will vary very much, being at a minimum when the crop has completed its work both of drying the soil and assimilating the nitrates present, and reaching a maximum in springtime after a winter drainage taking place in the absence of plant growth.

Applying these general principles to the cases before us, it is easy to see that the average proportion of nitrates in the drainage water passing through a soil growing leguminous crops will generally be greater than in cases where cereal crops are grown, the characteristic action of leguminous crops being to enrich the surface soil with nitrogen. The drainage water being richer, the proportion of nitrates in the subsoil out of reach of the changes produced by crop and season, will also be greater. The proportion of nitrates in the deeper subsoil of the vetch plot is in fact decidedly greater than in the subsoil of the wheat plots, and in the subsoil of the white clover plot the proportion of nitrates becomes quite considerable. In the case of the Bokhara clover and lucern plots, either the soil sampling has not been carried to such a depth as to reach the subsoil of constant nitrate content, or the drainage water in these plots is practically free from nitrates. For the very considerable amount of nitrate present in the white clover subsoil, there appear to be some special reasons. The crop on this plot was too small to cut in 1880, 1883, and 1884, and in other years only a single summer cutting was taken;

opportunity was thus given for the decay upon the land, and subsequent nitrification, of a considerable proportion of the produce. The roots of the white clover are also of shallower range than those of most leguminous crops, and thus have a very limited effect in removing nitrates from the soil during the period of growth.

Besides the analyses which I have just brought before you, determinations of nitrates have been made in soils which had grown barley, beans, and red clover. In each case it was evident that the crop had taken up more or less completely the nitrates of the soil. I need not, however, furnish further examples of this fact.

USE OF CROPS TO PREVENT LOSS OF NITRATES.

As the illustrations just given have shown the action of crops in appropriating the nitrates of the soil and thus preventing loss by drainage, we will pause here for a moment to say a few words on the means which a farmer has of diminishing the loss of nitrates in his soils. We have already seen that cereal crops, whose growing period is confined to the spring and early summer, are very poor conservers of soil nitrogen. Continuous wheat culture without manure will in fact soon impoverish a good soil. Permanent pasture, we saw in the second lecture, was the condition best suited to prevent loss of nitrates. We can not, however, have all our land in pasture. A greater amount of food and a far greater variety of produce can be obtained under arable culture; but we must recollect that as soon as the plow starts on its course the conditions which nature has established are destroyed, and we require the help of science if we are to work as economically as nature does under the altered conditions which we have introduced.

Experience, the result of experiment, has taught the European cultivator the advantage of rotations, which more or less fulfill the object of conserving soil nitrogen. In part they admirably answer the purpose. Thus when red clover is sown among a growing crop of barley and is left in full possession of the land when the barley is harvested, the effect is as nearly perfect as possible, the growth of the second crop succeeding the growth of the first without a break. In other forms of rotation, however, the sequence is very imperfect, as when turnips follow wheat. In such cases science demands that the land should be occupied by some crop during the autumn and winter. The farmer may in some cases rely upon the natural growth of weeds and leave the plowing of his wheat stubble till spring time, or he may sow his stubble immediately after harvest with rye or rape and feed this off in spring time before plowing or else plow it in. It is for the same reason undesirable for wheat to follow immediately upon a bare fallow, for the nitrates produced during the fallow are then left at the mercy of the autumn and winter rains. It is better to plant the fallow with mustard early in August and plow in the crop in October before wheat sowing. By proceeding thus the danger of losing the nitrates

contained in the fallow soil by autumn and winter drainage is much diminished.

We turn now after this digression to give illustrations of the quantity of nitrates occurring in soils cropped, and also receiving nitrogenous manures.

NITRATES IN SOILS CROPPED AND MANURED.

We have just noticed the striking absence of nitrates in the soil of a wheat stubble after harvest. I will now call your attention to the nitrates found in the soils of some of the plots of Broadbalk wheat field in the middle of October, 1881. The wheat was cut the second week in August. Immediately after there followed a deluge of rain, amounting in the month to 5.817 inches. The crop was not carted till September 1 and was much damaged. The land was scarified in the beginning of September and plowed toward the end of the month. The samples of soil were taken between October 10 and 18. The saturation of the soil by rain and the subsequent plowing had given nitrification a great start. It will be interesting before we consider the quantity of nitrates found in the various soils, to glance for a moment at the general course of nitrification as revealed by the composition of the drainage waters collected during this time, which we shall find in Table XI.

TABLE XI.—*Nitrogen as nitrates in the drainage waters of Broadbalk wheat field, August, 1881, to January, 1882, in parts per million.*

Plot.		Aug. 30.		Sept. 25.	Oct. 14.	Oct. 23.	Nov. 25.	Nov. 27.	Dec. 7.	Dec. 17, 18, 20, 21, mixed.	Jan. 9, 1882.
		6. 30 a. m.	2-3 p. m.								
3 and 4	No manure, 30-38 years.....	1.2	0.9	4.7	6.3	8.7	5.4	7.0	5.1	4.1	3.5
16	No manure, 17 years.....	.....	0.3	.....	7.4	8.6	5.1	6.3	4.1	3.4	2.9
5	Ash constituents, 30 years.....	1.5	1.4	6.0	8.1	9.5	6.0	7.3	6.3	5.0	3.9
17	Ash constituents, 1 year ...	1.0	0.4	8.8	9.6	10.7	5.4	6.8	5.6	4.1	3.7
6	Ash constituents, and ammonium salts 200 lbs.	.....	1.9	7.0	12.3	13.3	8.5	8.8	7.8	6.2	6.2
7	Ash constituents, and ammonium salts 400 lbs.	.....	4.1	.....	.....	18.5	9.8	11.7	10.9	7.3	7.2
8	Ash constituents, and ammonium salts 600 lbs.	.....	.....	.....	.....	23.0	17.1	18.2	16.8	11.2	10.2
10	Ammonium salts alone, 400 lbs.	20.3	16.1	20.6	21.0	16.2	11.2	14.5	14.0	9.3	9.1
11	Superphosphate, and ammonium salts 400 lbs.	9.0	6.8	10.7	12.6	19.6	12.6	14.9	13.7	9.4	9.4

The four plots which stand at the top of Table XI had received no nitrogenous manure; we have therefore no doubt that in these cases the nitrates were produced by the oxidation of the crop residue and of the organic matter of the soil. You see that the proportion of nitrates in the drainage waters from these plots is very small on August 30, becomes from four to eight times as great on September 25, reaches a maximum on October 23, and then gradually declines, the removal of nitrates by drainage proceeding more rapidly than their production during the last months of the year.

The progress of nitrification in the soil of plot 6, receiving 200 pounds of ammonium salts (in the spring) with a full supply of ash constituents, is quite similar to that observed in the case of the unmanured plots. The drainage on August 30 contains so small a proportion of nitrates that there is no reason to suppose that any nitrates derived from the ammonium salt remained unused in the soil at harvest time. The nitrates in this drainage water reach a higher maximum in October than is reached in the drainage water from the unmanured plots, but this is owing simply to the greater amount of nitrifiable organic matter (crop residue) present in the soil.

The drainage water from plot 7, receiving 400 pounds of ammonium salts with a full supply of ash constituents, starts with a distinctly higher proportion of nitrate; but it is doubtful whether even here there was any unused nitrate in the soil derived from the ammonium salt. Of the state of matters in the soil of plot 8, which had received the still larger amount of 600 pounds of ammonium salts, we have no certain information, as no drainage water was collected from this plot till October 23, but here certainly we should expect that unused nitrate remained in the soil at harvest.

A striking example of the presence of unused nitrate in the soil is furnished by plot 10. This plot receives the same quantity of ammonia as plot 7, but without any ash constituents, and no ash constituents had been applied to any part of the plot for thirty-one years at the time of which we are speaking. The result of this poverty in ash constituents is that the nitrates formed from the ammonium salts are only partially assimilated by the crop, the produce of wheat is comparatively poor (more than 10 bushels below that of plot 7), and in a dry season unused nitrate remains in the soil after the growth of the crop is completed. We see that the drainage water from this plot starts with a content of 20 parts per million of nitrogen as nitrates, and that instead of the quantity rapidly increasing and reaching a maximum by the end of October, it remains for a time nearly constant and then rapidly diminishes, the nitrification occurring in the soil being masked by the rapid removal of the ready-formed nitrates.

In plot 11 we have also ready-formed nitrate in the soil, but not nearly to the same extent as in plot 10. Here the ammonia is supplied with superphosphate, and there is consequently a partial supply of ash constituents; potash is, however, absent, and the crop is 7 bushels less than on plot 7.

With the information before us, supplied by the analyses of the drainage waters, we shall better understand the results afterwards obtained by the analysis of the soils. In Table XII will be found the quantities of nitric nitrogen, in pounds per acre found in the first, second, and third 9 inches of the soil of some of the plots in the wheat field.

TABLE XII.—*Nitrogen as nitrates in wheat soils variously manured, October, 1881, in pounds per acre.*

Plot.	Manuring.	First 9 inches.	Second 9 inches.	Third 9 inches.	Total 27 inches.	Excess over plots 3 and 4.
		<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>
3	No manure, 38 years.....	9.7	5.3	2.8	17.8	-----
4	No manure, 30 years.....	9.2	4.0	1.8	15.0	-----
16a	No manure, 17 years.....	10.6	5.0	2.3	17.9	1.5
5a	Ash constituents, 30 years.....	12.6	7.1	4.6	24.3	7.9
17a	Ash constituents, 1 year.....	10.3	7.5	3.4	21.2	4.8
6a	Ash and ammonium salts, 200 pounds.....	16.5	7.5	4.7	28.7	12.3
7a	Ash and ammonium salts, 400 pounds.....	22.8	11.3	5.7	39.8	23.4
8a	Ash and ammonium salts, 600 pounds.....	21.1	13.9	7.8	42.8	26.4
9a	Ash and sodium nitrate, 550 pounds.....	19.7	10.0	8.2	37.9	21.5
9b	Sodium nitrate, 550 pounds.....	16.3	20.1	17.7	54.1	37.7
10a	Ammonium salts, 400 pounds.....	14.2	11.9	7.3	33.4	17.0
11a	Superphosphate and ammonium salts, 400 pounds.....	17.9	9.3	3.6	30.8	14.4
19	Rape cake, 1,700 pounds.....	14.1	13.0	7.1	34.2	17.8
2	Farmyard manure, 14 tons, 38 years.....	30.0	15.4	6.8	52.2	35.8

The first point I would call attention to is the evidence which these figures afford that nitrification occurs principally in the surface soil. Notwithstanding the heavy rainfall that had taken place, and which had carried considerable quantities of nitrate into the subsoil, the first 9 inches still remain, save in one instance, by far the richest in nitrate. Taking the mean of the three unmanured plots, the relative proportion of nitrate in the three successive depths of soil is as 100, 48.5, and 23.4. In the plot heavily manured with farmyard manure the proportion is nearly the same, namely, 100, 51.3, and 22.7. Where, however, the soil had contained an excess of nitrate throughout the summer, it is now found at a lower level than the nitrate recently produced. The most striking instance of this is afforded by the soil of plot 9*b*, which receives sodium nitrate without ash constituents; here the quantity of nitrate in the second and third depths exceeds that in the first. In the case of plots 10*a*, 9*a*, 8*a*, and 19, the proportion of nitrates below the surface soil is also above the average, though to not nearly the extent shown by 9*b*.

Looking next at the total quantity of nitrate contained in these soils, we see that the smallest quantity is found in the unmanured land, amounting, on an average of three plots, to 16.9 pounds of nitric nitrogen in 27 inches of soil. On the plots where superphosphate and alkali salts are applied, but no nitrogenous manure, there is a distinct increase in the amount of nitrate found. This is not an isolated fact; it appears also in the analyses of the soils from the barley field. If we conclude that the addition of phosphates to the soil favors the process of nitrification, we shall be perfectly in accord with the results obtained in laboratory investigations upon nitrification.

When we turn to the soils receiving ammonium salts, we find that the amount of nitrate in the soil rises with the amount of produce yielded by the plot. In some cases the amount of nitrate varies almost exactly as the produce. Thus plots 7, 11, and 10 receive the same quantity of ammonia, but as they are very differently supplied with ash

constituents they yield very different amounts of produce. The average produce, as grain and straw, on these three plots during the thirty years preceding the soil sampling, was respectively 5,710, 4,387, and 3,450 pounds per acre. If we divide these quantities by the nitric nitrogen found in 27 inches of soil, we get as quotients—

$$\frac{5710}{39.8} = 14.3, \quad \frac{4387}{30.8} = 14.3, \quad \frac{3450}{33.4} = 10.3.$$

The proportion clearly differs in the last case, but this is the plot which contained at starting so much ready-formed nitrate. If now we take instead of the nitrate in 27 inches that in the first 9 inches, which at the time of soil sampling had been freed by rain from the nitrates originally present, we obtain an even series, the quotients being—

$$\frac{5710}{22.8} = 25.0, \quad \frac{4387}{17.9} = 24.5, \quad \frac{3450}{14.2} = 24.3.$$

The quantity of nitrate produced in the soil thus stands in close relation to the amount of the preceding crop, or rather to the amount of crop residue left in the soil.

The quantity of nitrate produced under the same conditions in various soils is not, however, wholly determined by the amounts of crop residue which they contain; the nitrates are in part produced from the old nitrogenous matter of the soil; and consequently in comparing the nitrate in unmanured soil with that found in soil liberally treated with ammonia and ash constituents, we find that the amount of nitrate bears a smaller proportion to crop residue in the latter than in the former case (*Jour. Roy. Agr. Soc.*, 1883, 360). In the present instance, where we are studying the commencement of nitrification, it is the most easily nitrifiable matter (crop residue) which chiefly determines the amount of nitrate produced. Later in the season the amount of nitrate formed in the various soils (not supplied with organic manure) would be much more alike.

The greater ease with which new supplies of organic matter nitrify as compared with the old humic matter of the soil, is further shown if we calculate the ratio of the nitric nitrogen to the total nitrogen of the soil. This ratio is always lowest in the case of the unmanured land, and the proportion of nitric nitrogen to total nitrogen rises with any increase in the crop or by the use of organic manures.

The largest quantity of nitric nitrogen found in the soil of any plot in the wheat field is, with two exceptions, to be presently mentioned, 42.8 pounds per acre; this is on plot 8, which gives the largest wheat crop in the field. A still larger amount of nitrate was found on plot 9b. The crop here was but small, but a large quantity of unused sodium nitrate remained in the soil from the manuring of the previous spring. On plot 2, which receives annually 14 tons of farmyard manure, the quantity of nitrogen as nitric acid amounted to 52.2 pounds per acre.

Looking at these results as a whole, we find in them a striking picture of the rapidity with which nitrates may be formed in a wheat stubble,

under favorable conditions, during the two or three months succeeding harvest. The example before us also supplies an instance of the great losses which such land may suffer from autumn and winter drainage. In Table XI we saw the composition of the drainage waters collected in Broadbalk field after the samples of soil were taken. According to the best estimate we can make from these analyses, an amount of nitrate equal to at least 60 per cent of that found in the soils in October, passed into the subsoil below the level of the drainpipes (2½ feet) by the end of the following January.

It is a question of much practical importance to what extent nitrates thus washed into the subsoil may become afterwards available for crops. If the subsoil is of an open texture, the water containing the nitrates will of course rapidly pass into the natural drainage outfalls and be entirely lost to the land. But if the subsoil is deep and retentive, a large amount of drainage water rich in nitrates may be stored at a considerable depth below the surface, of which fact we have already had illustrations in Table X. If these nitrates are to act as plant food, we need first a deep-rooted crop and next a dry season for its growth. Under these conditions a portion of the nitrates carried down by winter drainage are undoubtedly recoverable; but this is only possible when the subsoil is of the deep, retentive nature supposed. Land having such a subsoil clearly gains agricultural value.

We must next say a few words upon the quantities of nitrate found in some of the plots of the experimental barley field, which will be found in Table XIII.

TABLE XIII.—*Nitrogen as nitrates in barley soils variously manured, March, 1882, in pounds per acre.*

Plots.	Manuring.	First 9 inches.	Second 9 inches.	Third 9 inches.	Total 27 inches.	Excess over plot 10.
		<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>	<i>Pounds.</i>
10	No manure	5.9	4.7	5.1	15.7	-----
20-40	Ash constituents (mean)	6.7	7.0	6.4	20.1	4.4
1 A	Ammonium salts, 200 pounds	6.1	8.3	7.0	21.4	5.7
2 A-4 A	Ammonium and ash constituents (mean)	7.7	7.8	7.6	23.1	7.4
1 A A	Sodium nitrate, 275 pounds	9.7	6.8	9.0	25.5	9.8
2 A A-4 A A	Sodium and ash constituents (mean)	8.3	7.4	7.5	23.2	7.5
1 C	Rape cake, 1,000 pounds	10.6	13.7	7.9	32.2	16.5
2 C-4 C	Rape cake and ash constituents (mean)	8.8	11.9	8.7	29.4	13.7
71	No manure 10 years, formerly dung	14.8	11.8	10.9	37.5	21.8
72	Farmyard manure, 14 tons	18.6	14.6	10.9	44.1	28.4

The soil of the barley field was not sampled till March (1882), after a wet autumn and winter. We have thus not to do, as in Broadbalk field, with the first active stage of nitrification, but with the residue of nitrates remaining after the soil had suffered a considerable amount of washing.

The first point which strikes one on looking at these figures is the even distribution of the nitrates through the soil. In the case of Broadbalk wheat field, sampled in October, the average proportion of nitrate in the first, second, and third 9 inches (omitting plot 9b) is 100, 59, and

31. In Hoos barley field, sampled in the following March, the nitrate is distributed through the same three depths in the proportion of 100, 102, and 88. It is only in the case of the two plots which had received farmyard manure that the largest amount of nitrate is found in the first 9 inches of the soil.

The distinctions due to differences in manuring or to differences in the amount of crop residue, are much smaller than we have already noticed in the case of the wheat field, partly because smaller quantities of nitrogenous manure are applied to the barley than to wheat, and partly because the excessive autumn and winter rains have removed much of the nitrate produced during the active stage of nitrification. The most striking results we observe are, (1) that manuring with ash constituents alone increases the production of nitrates in the soil; (2) that the bigger crops grown by ammonium salts or sodium nitrate, with ash constituents, are followed by an increased production of nitrates; (3) that the use of an organic manure like rape cake or farmyard manure, is attended with a large increase in the production of nitrate, even after the first active stage of nitrification is long past.

Rape cake has been used as a manure to a much larger extent in the barley than in the wheat experiments. In the barley experiments powdered rape cake has been applied annually to four plots since the commencement in 1852. The produce obtained, although good, has not equaled that yielded by ammonium salts or sodium nitrate, supplying a rather smaller quantity of nitrogen. The effect on the soil has, however, been very marked. The plots manured with rape cake contain in the first 9 inches a higher percentage both of nitrogen and carbon than any other plots in the field, with the exception of those receiving farmyard manure. The nitrogenous organic matter of the rape cake nitrifies much more slowly than ammonia, and thus does not supply as much plant food during the period of the active growth of the barley as is supplied by ammonium salts or sodium nitrate. With the rape cake, nitrification extends more evenly throughout the year, and nitrates are thus produced when they are not wanted.

The plots which have received farmyard manure show, as in the wheat experiments, the largest amount of nitrification; in the barley experiments there is, however, a point of special interest. After twenty years' continuous application of farmyard manure the plot was divided and one half has since received no manure. The sampling of the soil took place ten years after the application of farmyard manure had ceased. The effect of the residue of the previous manuring was, however, still very apparent. The soil contained both more nitrogen and more nitric acid than any other plot, save the one continuously treated with farmyard manure. We have here a striking example of the slowness with which residues of farmyard manure decompose in a clay soil. The effect of the old manuring is very distinctly seen in the crop.

NITRIFICATION OF MANURES.

A good deal has already been said, incidentally, on the subject of the nitrification of manures, but some facts remain to be noticed. The manures most readily nitrified by a fertile soil are the salts of ammonium; of these, I need hardly tell you, the sulphate is the one most generally employed in agriculture. At Rothamsted it has been usual to employ a mixture of equal weights of the sulphate and chloride. The use of the chloride is attended with considerable advantages if an examination of drainage waters is included in the experiment. Chlorine not being retained by the soil but passing away freely in the drainage, its proportion in the drainage water becomes a very convenient indication of the movements of soluble salts in the soil.

For sulphate or chloride of ammonium to nitrify, it is essential that the soil should contain a certain proportion of calcium carbonate. There are some soils upon which ammonium sulphate produces very little effect as a manure. When this is the case it will generally be found, I think, that the soil is deficient in a salifiable base.

When sulphate or chloride of ammonium is applied to a fertile soil the first action which takes place is purely chemical. The salt is decomposed by the calcium carbonate, the operation being greatly aided by the fact that the ammonium carbonate is removed out of solution as fast as it is produced, becoming united to the humic matters, to the hydrated ferric oxide, and to certain hydrated silicates in the soil. The ammonia is thus fixed by the soil, while the sulphuric acid or chlorine combines with calcium, and is ready to pass at once into the drainage water.

I can not better illustrate the series of changes which occur than by giving you the results of the analysis of drainage waters from one of the plots of Broadbalk field, collected at frequent intervals after the application of ammonium salts to the land. On October 25, 1880, ammonium salts at the rate of 400 pounds per acre (half chloride) was applied to plot 15 and plowed in. Heavy rain occurred on the night of the 26th, and on the morning of the 27th the drainpipe of the plot was running. Rain occurred afterwards at frequent intervals, so that a series of drainage waters was collected, the earliest collection being about forty hours after the application of the ammonium salts. In Table XIV the composition of these runnings is compared with that of the drainage collected on October 10, before the application of the ammonium salts.

TABLE XIV.—Composition of the drainage water of plot 15 before and after the application of ammonium salts on October 25, in parts per million.

Date of collection.	Nitrogen as ammonia.	Nitrogen as nitrates.	Chlorine.	Nitrogen as nitrates to 100 chlorine.
1880, October 10.....	None...	8.2	22.7	37.0
1880, October 27, 6:30 a. m.....	9.0	13.5	146.4	9.2
1880, October 27, 1 p. m.....	6.5	12.9	116.6	11.1
1880, October 28.....	2.5	16.7	95.3	17.5
1880, October 29.....	1.5	16.9	80.8	20.9
1880, November 15, 16.....	None...	50.8	54.2	93.7
1880, November 19, 26.....	Do.....	34.6	47.6	72.7
1880, December 22, 29, 30.....	Do.....	21.7	23.2	93.5
1881, February 2, 8, 10.....	Do.....	22.9	19.4	118.0

You will see that at the first running of the drainpipe sufficient time had not elapsed for the complete decomposition of the ammonium salt and the fixation of the ammonia. Some undecomposed salt of ammonium is thus found in the earlier drainage waters—a circumstance which is very unusual. That decomposition of the salt had already taken place to a very large extent, is shown, however, by the enormous amount of chlorine in the first runnings, an amount far exceeding that of the ammonia.

Even at this early stage of the reaction, only forty hours after the application of the ammonia, nitrification has made a distinct commencement, the first running containing 13.5 parts of nitric nitrogen per million, while in the last running preceding the application of the ammonia only 8.4 parts per million were present.

The proportion of nitrate increases in the successive drainage waters obtained, the maximum of nitrate being reached three weeks after the application of the ammonia. We shall see in the next lecture that the occurrence of this maximum of nitrate in the drainage water does not in itself amount to a proof that the nitrification of the ammoniacal manure was then completed, but the facts which I shall presently mention show that only a short time is required for the complete nitrification of an ammonium salt.

The proportion of nitrate to chloride continues to increase as the season advances, the amount of chloride being steadily diminished by loss through drainage, while the quantity of nitrate is partially maintained by the constant nitrification of the soil.

The most complete experiments upon the nitrification of ammonium salts by soil are those of Schlösing. In his earlier experiments with ammonium chloride (*Chimie Agricole*, 165), 111.3 and 114 parts of ammonia were added in solution to a million of soil. In eighteen days 89.3 and 88.1 per cent, respectively, of the ammonia had disappeared, while nitric acid equivalent to 105.5 and 114.1 per cent of the ammonia had been produced. Some nitrification of the soil had thus taken place side by side with the nitrification of the ammonia. In a later experiment with ammonium chloride (*Compt. rend.*, 109, 423), in which a ten

times greater proportion of the salt was used (1,136 parts of ammonia per million of soil), but little nitrification took place during the first fourteen days; during the next thirty-two days nitrification was very active. The experiment closed after a total of fifty-seven days. At this time 85.6 per cent of the ammonia had disappeared and nitric acid equivalent to 83.7 per cent of the ammonia had been formed. No nitrification of the organic matter of the soil had thus occurred.

In an experiment of my own it also appeared that nitrification of the soil was retarded in the presence of ammonium chloride. Two equal masses of moist, powdered soil were taken, one receiving ammonium chloride equivalent to 70 parts of ammonia per million of air-dried soil, the other receiving no ammonia. At the end of one hundred and nineteen days both soils were analyzed. It was found that 97.6 per cent of the ammonia had disappeared. The nitric acid produced in the manured soil was considerably in excess of the ammonia which had disappeared, but the nitrification of the soil in this case was only 83.6 per cent of that occurring in the absence of the ammonia. Thus, as we have already had occasion to state, the most easily nitrifiable substance in a mixture is always the first which nitrifies.

With sulphate of ammonium Schlösing obtained a more rapid nitrification than with the chloride. Using 694 parts of ammonia per million of soil, active nitrification commenced in two days and lasted eight days. The experiment ended in twenty-two days. It was then found that 98.6 per cent of the ammonia had disappeared. The nitric acid produced was 96.4 per cent of the ammonia. Here again, therefore, there had been no nitrification of the soil.

Schlösing also made three experiments with carbonate of ammonium, using 526, 1,271, and 2,251 parts of ammonia per million of soil. The duration of the nitrification was, respectively, twenty-eight, thirty-seven, and eighty-six days. The ammonia in all cases disappeared very thoroughly, the proportion converted being 97.7, 99.2, and 97.6 per cent. The nitric acid produced was in all cases less than the ammonia which had disappeared, the products being, respectively, 95.6, 94.6, and 80.6 per cent of the ammonia. In all these experiments errors from volatilization of the ammonia have been carefully guarded against. In each case also it has been ascertained whether free nitrogen was produced in the course of the reaction. On this point negative results were obtained, save where the larger amounts of ammonium carbonate had been employed. With the largest quantity of ammonium carbonate the nitrogen evolved was equal to 8.7 per cent of the ammonia; with the intermediate quantity the nitrogen amounted to 3.4 per cent. Schlösing believes that the evolution of free nitrogen is connected with the presence of nitrites in the soil, and he shows that when calcium or ammonium nitrite was added to the soil which he employed some evolution of free nitrogen occurred. The nitrogen evolved amounted to 7

per cent of the nitrogen in the calcium nitrite, and to 5.9 per cent of the nitrogen added as ammonium nitrite. The true explanation of these results is as yet uncertain.

The nitrification of manures other than ammonium salts has at present been very insufficiently studied; experimenters have frequently made the mistake of employing the manure they were investigating in far too large a quantity in relation to the mass of soil taken, and their results have consequently been of an abnormal character.

The experiments of C. F. A. Tuxen afford striking examples of the fact that when nitrogenous organic manures, as bone meal and fish guano, are mixed with soil, the production of ammonia precedes the formation of nitric acid.

In Dehérain's experiments with farmyard manure, the most sustained nitrification was obtained where the soil contained about 15 per cent of water; both with wetter and drier soils the final result was less. In the best experiment about 59 per cent of the nitrogen of the manure was nitrified in one hundred days; the results were, however, very irregular.

We have already seen that in the Rothamsted experiments a very large amount of nitrates was found in the soils continuously manured with farmyard manure; the drainage water from the farmyard-manure plot in Broadbalk field is not, however, rich in nitrate. The cause of this discrepancy is at present uncertain.

Perhaps the most interesting of recent experiments on the nitrification of manures are those by Müntz and Girard (*Ann. Agron.*, 1891, 289). These investigators place guano next to ammonium salts in the order of nitrifiability; following guano come green manures (lucern and lupines), which, compared with other forms of manure, appeared to be especially active in clay soils; the third class includes dried blood and meat, and powdered horn; far below these stand poudrette, wool, and leather.

The effect of inorganic salts upon nitrification has been made the subject of a few experiments. Schlösing added various salts to soil in quantities not exceeding 485 parts per million; such doses had no apparent effect on the rate of nitrification. Dehérain, using larger proportions, found that common salt began to be harmful when it exceeded one thousandth of the weight of the soil, and with larger quantities nitrification almost ceased. The addition of sodium nitrate, according to the same observer, may stop nitrification for a time, but it afterwards recommences.

LECTURE VI.

DRAINAGE AND WELL WATERS.

Movements of salts within the soil—Drainage by open channels and by displacement—The substances removed in drainage water—Alterations in composition at different seasons—The deep well waters of Harpenden: (1) Incontaminated wells; (2) contaminated wells; (3) mineral constituents of the water—Conclusion.

Before considering the chemical composition of the drainage waters from manured land we must in the first place try to obtain a clear idea of the general behavior of water and salts in a mass of soil both in a state of rest and when fresh supplies of water or salts are received from without.

MOVEMENTS OF SALTS WITHIN THE SOIL.

Although we can easily conceive a state of rest within the soil during which no motion takes place in the mass of water which the soil contains, it is of course a condition which rarely if ever happens; it will simplify the question, however, if we regard in the first instance the actions which would occur during a state of rest.

When there is no movement in the mass of water in a soil, the movements of the dissolved salts are determined solely by the laws of diffusion. The action of these laws has been frequently overlooked.

Molecular diffusion will affect chiefly those salts which remain permanently in a state of solution in the soil; it will affect chlorides and nitrates, and in a less degree, sulphates; it will affect salts of sodium and calcium; it can only have a temporary and partial effect upon phosphates or upon salts of ammonium or potassium, because phosphoric acid and the bases just named are sooner or later fixed by the soil. Molecular diffusion will affect different salts in a different degree, according to their respective diffusive power; thus, sodium nitrate will diffuse more rapidly than calcium nitrate, a fact of practical importance, establishing a difference between the action of ammonium salts and sodium nitrate in the soil. Molecular diffusion will also increase in rapidity as the temperature rises. The final outcome of molecular diffusion is the equal distribution of the soluble salts through the whole mass of water contained in the soil.

The practical effects of diffusion are considerable. A dressing of sodium nitrate applied to a moist soil begins to distribute itself before

rain takes place. Again, when heavy rain has washed all soluble salts out of the surface soil they will begin slowly to return as soon as rain has ceased. Or again, when by the action of a root the soil solution has become locally exhausted of any particular salt, diffusion will constantly tend to supply this deficiency.

We turn next to the far more rapid changes produced by movements of water within the soil. These movements of water may be upward or downward.* The water may rise by capillary attraction to replace the loss by evaporation at the surface or to replace the water taken up by roots. On the other hand the water may descend through a permeable soil, in consequence of rain falling on the surface. The latter is the movement with which we are at present chiefly concerned. We will consider in the first place the simplest case, where the soil is permeable and homogeneous and therefore free from channels and fissures. The result of the continuous application of water to the surface of such a soil will be very different, according as the soil was at starting dry or wet. The water in each case descends through the soil as a column, pushing before it the solution of salts which the soil contains; but the bulk of the solution to be expelled depends entirely on the quantity of water already present in the soil. If we make a laboratory experiment with dry, powdered soil and increase the rate of percolation by the use of pressure, so as to get rid as far as possible of the effects of diffusion, we find that the whole of the soluble salts is expelled in a small volume of highly concentrated solution. I have already mentioned to you (Lecture IV) an experiment in which three quarters of the soluble salts in 7 pounds of dry soil 8 inches deep, were expelled in the first 50 c. c. of water which came through. If instead of a dry soil we take a soil saturated with water, percolation will begin with the first application of water to the surface, but the solution expelled will now be a weak one and the salts present will be entirely removed only when the whole volume of water originally present in the saturated soil has been pushed out by the new application of water at the surface. If during the experiment time is allowed for diffusion, a still larger proportion of water will be required to expel the soluble salts present.

I can not better illustrate the diffusion of salts in a soil and also the mode in which soluble salts applied to the surface are expelled in the drainage water, than by giving you the results of a laboratory experiment in which common salt was first applied to the surface of a saturated soil, forming a column 8 inches deep, and then removed in the drainage water by regular applications of pure water at the surface. The arrangement of the experiment has already been described in the fourth lecture (p. 70). The soil at starting was free from chlorides. The percolation was

* There may also be side currents of water in the soil; of these we have an excellent illustration in the movement of the underground water supplying the deep wells at Harpenden, p. 105.

perfectly natural, the air pump being used only during the preliminary saturation of the soil with water.

After the weighed quantity of pure sodium chloride had been applied to the surface of the saturated soil, a week was allowed to pass before further steps were taken. After this time 120 c. c. of pure water were daily placed upon the soil and a nearly equal quantity of drainage water removed and analyzed. The results of the analysis of each day's drainage are shown in Table XV.

TABLE XV.—*Results of percolation after sodium chloride containing 233 milligrams of chlorine had been applied to the soil.*

Water put on.	Drainage obtained.	Chlorine in drainage water.	
		Per million.	Milligrams.
<i>Grams.</i>	<i>Grams.</i>		
120	117.1	None.	None.
120	119.4	None.	None.
120	115.1	None.	None.
120	120.2	43.8	5.3
120	115.3	202.0	23.3
120	118.9	476.0	56.6
120	114.0	621.0	70.8
120	123.4	425.0	52.5
120	118.9	158.0	18.8
120	120.0	39.8	4.8
120	119.4	7.6	0.9
1,320	1,301.7		233.0

It will be seen that during the first three days the drainage water obtained was free from chlorine. On the fourth day, something less than 471.8 grams of drainage water having passed, the discharge of the chlorine commenced. We have here at once evidence of the downward diffusion of the chloride during the eleven days that had passed since its application. If no diffusion had taken place and the chloride had remained at the surface, it would have required the application of 850 grams of water to cause its appearance in the drainage, this being the amount of water necessary to displace the water already held by the soil. The chloride having already descended a considerable distance, the displacement of about 400 grams of water was sufficient to bring some of it into the drainage water.

It will be seen that it took eight days to remove all chloride from the soil and that the drainage water containing chlorine amounted to 950.1 grams, a quantity in striking contrast to the 150 grams of drainage in which the whole of the chlorine was contained when water was quickly drawn through a similar weight of air-dried soil by the air pump.

On looking at the strengths of the successive runnings, it will be evident that the chloride came through the soil as a wide band, diffusing both at its lower and upper edges. This is the usual mode in which diffusible salts descend through a soil, and a knowledge of this fact is essential if we are to understand the results of the analyses of drainage waters collected within a moderate distance of the surface.

The phenomena of drainage are much complicated in a natural soil by the fact that such soils always contain a multitude of fissures, consisting of cracks in the soil and channels formed by worms or left by decaying roots. These fissures communicate directly with the surface, and down them water passes which has never permeated the whole mass of soil. The result is that the drainage collected at a moderate distance below the surface is a mixture of two waters of different composition, and at different periods in the running one or other of these waters will greatly preponderate.

During the months of March and April, 1879, the nitrate present in the drainage from the soil of the 5-foot drain gauge was determined daily. When no rain had occurred the small amount of drainage water collected had a very uniform composition, containing 14 to 15 parts of nitrogen per million of water. Whenever rain fell to the extent of 0.1 inch the discharged water became much weaker, the nitrogen as nitrate falling several times to 7 to 8 parts per million. When rain ceased the previous strength of 14 to 15 per million was soon regained. The rain, thus, did not simply displace the solution of nitrate contained in the soil; such an action doubtless took place, but there was at the same time a discharge of water which had come directly from the surface and which was far poorer in nitrate than the water which had percolated through the soil.

In the case just mentioned the dry weather drainage was the strongest and the end of a running was stronger than the beginning. This is the most usual condition of things; it is the order generally observed in the runnings of the drainpipes in Broadbalk field. But this order may be entirely reversed when soluble salts have been recently applied as manure to the surface. The direct channel drainage, bringing water directly from the surface, will then be stronger than the water which had percolated through the soil, and the beginning of a running will be stronger than the end of it. In Broadbalk field a change from this condition of things to that first named is observed every year upon the plots receiving ammonium salts if sufficient rain occurs.

In Table XVI you will find examples of the alteration in the composition of a drainage water during the running of the drainpipes. The first hour named in each group of analyses is the time* of the first collection from the drainpipes; at the last hour named rain has long ceased and the water has nearly ceased to flow.

*The drainpipes in Broadbalk field do not discharge water in consequence of the water level in the subsoil rising to the level of the pipes; this is forbidden by the fact that the subsoil lies on chalk. The drainage water collected is a discharge from the saturated soil above and around the pipe, with the addition of a variable proportion of water which has come by channels directly from the surface. The pipes stop running a few hours after rain has ceased.

TABLE XVI.—*Alteration in composition of drainage waters from Broadbalk field during their running.*

PLOT 13, AMMONIUM SALTS APPLIED MARCH 12, 1879.

Date of collection.		Chlorine per million.	Nitrogen as nitric acid per million.
April 7—	7 a.m.	101.4	29.4
	9 a.m.	70.0	20.1
	11 a.m.	57.8	16.1
	1 p.m.	50.0	14.0
April 13—	4 p.m.	41.2	11.5
	2 p.m.	79.0	34.2
	4 p.m.	66.2	23.9
	6 p.m.	60.2	20.7
May 29—	7 a.m.	67.3	9.9
	10 a.m.	76.0	13.4
	1 p.m.	63.8	16.6
	5 p.m.	65.1	12.5
June 2—	9 p.m.	33.9	4.3
	3—7 a.m.	63.1	7.9
July 1—	10 a.m.	22.9	0.5
	2 p.m.	34.7	0.9
	8 p.m.	36.7	0.9
August 3—	8 a.m.	18.4	0.0
	10 a.m.	20.8	0.2
	4 p.m.	25.3	0.4

PLOT 15, AMMONIUM SALTS APPLIED OCTOBER 25, 1880.

October 27—	6:30 a.m.	146.4	13.5
	1 p.m.	116.6	12.9
October 20—	10:30 a.m.	80.8	16.9
	4 p.m.	66.6	14.0
November 15—	4 p.m.	39.0	67.8
	16—8 a.m.	60.6	50.0
	4 p.m.	63.1	34.6

In the case of plot 13 the ammonium salts (half chloride) were applied to the land as a top-dressing on March 12. On the occasion of the next running of the drainpipes, on April 7, there is a wonderful difference in composition between the water first collected at 7 a. m. and that last collected at 4 p. m., the last collection of water having less than half the strength of the first. When the drainpipe again flows, on April 13, the water starts with a much greater content of chlorine than it left off with at the close of the preceding running. The chlorine again diminishes considerably at the close of the running, but the change is by no means so great as before. On May 29 we are at the turning point between the two modes of alteration in the drainage water. The band of chloride is now but little above the level of the drainpipe. On June 2 we have passed into the more usual mode of alteration, which now continues until the next application of ammonium salts to the land. The surface soil now contains less chloride than the soil immediately above the pipe, and the drainage water consequently always increases in strength toward the end of the running.

The movement of the soluble salts in a soil can be studied with greater ease and exactness from observations of the chlorides than from observations of the nitrates, as the latter are at all times being

produced in large quantities near the surface, and at times are being rapidly removed by growing crops. Owing to this essential difference between the nitrates and chlorides it is possible for the nitrate content of a drainage water to alter during the running in a contrary direction to that shown by the chlorides. An example of this is furnished at the bottom of Table XVI. Plot 15 had received its ammonium salts on October 25; heavy rain followed from the 26th to the 29th; the chlorides were thus washed into the subsoil before any considerable nitrification had taken place. By November 15 the surface soil had become rich in nitrates, the chlorides occupying a much lower level. It followed in consequence that during the running of November 15 and 16 the nitrate decreased toward the end of the flow while the chlorides increased. For a fuller study of these facts see *Jour. Roy. Agr. Soc.*, 1882, 15.

THE SUBSTANCES REMOVED IN DRAINAGE WATER.

We must now say a few words as to the substances removed in drainage waters. We are indebted to Dr. Voelcker and to Dr. Frankland for the determination of the constituents other than chlorine and nitric acid contained in the Rothamsted drainage waters.

Dr. Frankland's analyses of water both from the drain gauges and from Broadbalk wheat field show that even the clearest drainage waters contain a small quantity of dissolved organic matter very nitrogenous in composition, the ratio of nitrogen to carbon being 1:2.6 in the case of clear water from the unmanured soils of the drain gauges, and 1:3 in the case of clear water from the wheat field. In turbid waters, consisting chiefly of water which has come directly from the surface through open channels, the proportion of organic matter is greater, and it is considerably richer in carbon.

The principal dissolved constituent in the drainage water from unmanured land is calcium carbonate. Any application of manure increasing the fertility of the land increases also the proportion of calcium carbonate in the drainage water, the amount of carbonic acid in the soil rising with the amount of crop residue annually undergoing decomposition. With the application of artificial manures there is a large increase of other salts of calcium. Superphosphate naturally produces an increase of calcium sulphate. When with the superphosphate the sulphates of potassium and sodium are applied, there is a further increase of calcium sulphate, resulting chiefly from the decomposition of the potassium sulphate in the soil. When ammonium salts are added there is a large increase in calcium salts, the acids of the ammonium salts combining with the lime of the soil. There is, further, a production of calcium nitrate when the ammonium undergoes nitrification.

The loss of calcium carbonate which a soil suffers when continually manured with ammonium salts is a point which should always be borne in mind. It has been found necessary at Rothamsted to apply a heavy dressing of chalk or lime to those plots in the grass experiments which

had long received ammonium salts. In the absence of calcium carbonate the action of ammonium salts on pasture is injurious rather than beneficial. One result of the presence of so large an amount of calcium salts in the drainage waters from the plots receiving ammonium salts is that these waters are remarkably clear, the calcium salts maintaining the coagulated condition of the clay.

If we take the mean of ten series of analyses of drainage waters by Voelcker and Frankland (1866-73), and assume the average drainage in Broadbalk field as 10 inches per annum, we have 223 pounds of lime and magnesia as the annual loss per acre upon the unmanured plot; 297 pounds on the plot receiving superphosphate, with sulphates of potassium, sodium, and magnesium; 284 pounds on the plot receiving sodium nitrate, with half a dressing of superphosphate and alkali sulphates; 389 pounds on the plot manured with ammonium salts only; 443 pounds where superphosphate is used with the ammonium salts; and a mean of 485 pounds where alkali sulphates are also applied.* These figures are of course approximate only. The amount of lime supplied in the superphosphate is about 86 pounds per acre.

On the plot receiving sodium nitrate there is no such loss of lime in the drainage water as is found when ammonium salts are applied.

The amount of phosphoric acid found by Voelcker in the drainage water was very small and irregular. A mean of all the analyses would show a loss of 2.1 pounds per acre for 10 inches of drainage.

The amount of potash found in the drainage waters was larger. Where no potash was applied in the manure the annual loss, supposing 10 inches of drainage, would be 3.6 pounds, and where potassium salts had been made use of, 9.5 pounds per acre per annum. In the absence of drainpipes the greater part of both potash and phosphoric acid would doubtless have been retained by the subsoil.

Soda was present in the drainage waters in much larger quantity than potash, and where soda had been applied in the manure the quantity in the drainage waters was much increased. The chemists who have made a study of the retentive powers of soil have told us that soda is a substance on which soil exerts but little influence. This and other established facts respecting the retentive power of soil are excellently illustrated in the case of the Broadbalk drainage waters.

We may obtain evidence of the retention or non-retention by the soil or crop of the substances applied in the manure by comparing the relative proportion of the constituents present in the manure with the relative proportion of the same constituents found in the drainage water. If none of the constituents of the manure has been abstracted by the soil or crop, we shall find that these constituents will bear the same

* The quantities of the manures per acre are as follows: Superphosphate $3\frac{1}{2}$ cwt., potassium sulphate 200 pounds, sodium sulphate 100 pounds, magnesium sulphate 100 pounds, sodium nitrate 550 pounds, ammonium salts (half chloride, half sulphate) 400 pounds.

proportion to each other in the drainage water as in the manure, while any assimilation by the crop or retention by the soil will lower the proportion of the constituents thus appropriated in the drainage water. Thus in the case of seven plots receiving phosphoric acid, the mean proportion of sulphuric acid to phosphoric acid in the manures was 1000:194, but in the drainage water from these plots the proportion was 1000:17, showing a large retention of the phosphoric acid. Again, taking six plots receiving potassium sulphate, we find that the mean relation of sulphuric acid to potash in the manure was 1000:273, while in the drainage water from these plots the relation was 1000:50, showing a consumption or retention of more than four fifths of the potash. On the other hand, the relation of sulphuric acid to soda in the manure of seven plots was 1000:253, while in the drainage water the relation stood as 1000:271, showing that a little more sulphuric acid than soda had been taken up. In the manure of nine plots the relation of sulphuric acid to chlorine was 1000:367, in the drainage waters therefrom the proportion was 1000:382, showing that rather more sulphuric acid than chlorine had been retained.

ALTERATIONS IN COMPOSITION AT DIFFERENT SEASONS.

As the time at our disposal is now short, I will speak of the alterations in composition occurring at different seasons of the year only as they affect the most important constituent of the drainage waters—that is the nitrates. We have already traced the course of change throughout the year exhibited by the nitrates in the drainage from the uncropped or unmanured soils of the drain gauges, and again in the drainage from the unmanured plot in the wheat field. We have still to speak of the changes which occur when manure is applied to the land.

In Table XVII the average proportion of nitrogen as nitrates in the drainage waters from the principal plots in Broadbalk field is given for a period of five years, during which the whole of the ammonium salts was applied in the spring, save in the case of plot 15, which is placed in the lower division of the table. In this table the year is divided into four periods, (1) the spring period, from the time of top-dressing with ammonium salts or sodium nitrate in March to the end of May; (2) the summer period, from the beginning of June to harvest; (3) the autumn period, from harvest to autumn sowing of manures* before drilling the wheat; (4) the winter period, from autumn sowing to March.

* The manures supplying ash constituents are plowed in during October, and at this time the nitrogenous manures mentioned in the lower division of the table were also applied.

TABLE XVII.—*Nitrogen as nitrates in the drainage waters from variously manured wheat plots—average of five years, 1878-83, in parts per million.*

NITROGENOUS MANURES APPLIED IN MARCH.

Plots.	Manuring.	March to end of May.	June to harvest.	Harvest to autumn sowing.	Autumn sowing to March.	Whole year.
3 and 4	No manure	1.7	0.1	5.6	3.9	3.5
5	Ash constituents	1.7	0.2	5.6	4.5	3.9
6	Ash constituents and ammonium salts, 200 pounds.....	8.1	0.7	7.3	4.8	5.0
7	Ash constituents and ammonium salts, 400 pounds.....	16.3	1.4	8.3	5.2	6.4
8	Ash constituents and ammonium salts, 600 pounds.....	21.5	4.0	14.7	7.3	9.3
9	Ash constituents and sodium nitrate, 550 pounds.....	48.4	9.1	14.3	6.8	12.3
10	Ammonium salts, 400 pounds	28.6	11.4	11.5	6.3	9.9
11	Superphosphate and ammonium salts, 400 pounds.....	19.5	5.8	9.2	7.1	8.5

NITROGENOUS MANURES APPLIED IN OCTOBER.

15	Ash constituents, ammonium salts, 400 pounds.....	5.7	2.9	7.4	26.4	19.4
19	Rape cake, 1,700 pounds.....	4.7	0.5	8.2	12.5	10.1
2	Farmyard manure, 14 tons	2.7	1.4	7.4	7.3	5.6

On two plots, placed at the top of the table, no nitrogenous manure is applied. Here the spring period shows a considerable diminution in the amount of nitrates in the drainage water, which is followed by their almost entire disappearance in summer. Autumn shows the maximum amount of nitrates for the year, and winter stands second in the richness of the drainage water. The plot receiving ash constituents shows a little more nitrate in the drainage water than the permanently unmanured land.

On plots 6, 7, and 8 rising quantities of ammonium salts are applied, and also a full supply of ash constituents. Here and on all the other plots receiving ammonium salts in March, the drainage water is richest in nitrates during the spring months. Very considerable losses of nitrate occur on these plots if much rain falls in April. On plots 6 and 7, where the ammonia is not in excess of the assimilating power of the crop, the nitrate will disappear from the drainage water in May if the season be an early one or else in June or July. After harvest there is usually no unused nitrate remaining in the soil, the small excess of nitrate shown in the drainage water during the autumn months being simply due to the larger crop residue undergoing nitrification. The very similar amount of nitrate passing away during the winter months from plots 5, 6, and 7, to the first of which no ammonia is applied, is a striking illustration of the well-known fact that ammonium salts leave no residue in the soil which is of use to the next season's crop.

Plot 8 receives the largest quantity of ammonium salts applied in the field. The quantity is in excess of the requirements of the crop, and

therefore nitrates never entirely disappear from the drainage water during the summer months, and some residue of nitrates is found after harvest, which, however, is soon removed by the autumn rains.

On plots 10 and 11 we have the same weight of ammonium salt applied as on 7, but with deficient ash constituents, plot 11 receiving only superphosphate and plot 10 no ash constituents whatever. The drainage waters from these plots reveal in a striking manner the waste of nitrates which occurs when the crop is not fully supplied with ash constituents. The waste is naturally greater on plot 10; here the drainage water contains the largest amount of nitrates during the spring and summer months of any plot in the field receiving salts of ammonia.

On plot 9 sodium nitrate is applied, the dressing containing approximately the same amount of nitrogen as 400 pounds of ammonium salts. During the five years to which the results in the table refer, the sodium nitrate was applied as a top-dressing at the same time as the ammonium salts. Unfortunately for the purposes of comparison, only one half of plot 9 receives ash constituents; one half is thus in a similar condition to plot 7, while the other half resembles plot 10. The result shown by the drainage water is, however, so marked as to leave us in no doubt as to the comparative losses which attend the use of sodium nitrate and ammonium salts. The liability to loss by drainage during the spring months is clearly greater with nitrate of sodium than with ammonium salts. It is a striking evidence of the excellence of the nitrate as a manure that notwithstanding the greater losses which it suffers during the spring months, it should, on an average of seasons, give a larger produce than ammonium salts for the same amount of nitrogen supplied.

In the lower division of the table we have the composition of the drainage waters from plots which receive their nitrogenous manure in the autumn. Plot 15 receives exactly the same manure as plot 7 in the upper division of the table, but the ammonium salts are applied in October. Under these circumstances the drainage water is richest in nitrates during the winter months, and as this is the time when drainage is most excessive and the wheat plant least capable of assimilating nitrates, the loss is in most seasons very great. The loss of manure is distinctly reflected in the crop, which in an average of seasons is decidedly less than that on plot 7. Plot 15 supplies us, however, with the best examples of the recovery of nitrates by the crop after they have been washed below the level of the drainpipe, for when a wet winter is followed by a dry spring and summer a marked improvement of the crop sets in, and the result at harvest is far better than was anticipated.

The drainage water from the plot manured with rape cake in October shows, in a much smaller degree, the same characteristics as the drainage from plot 15, just considered. The drainage from the farmyard-manure plot is but scanty and certainly does not contain the amount of

nitrates which we should expect, having regard to the large amount found in the soil when analyzed in October, 1881 (Table XII). Either the water collected from the pipe does not accurately represent that percolating through the soil (*Jour. Roy. Agr. Soc.*, 1882, 6, 35), or the nitrates on this plot are destroyed by reduction to nitrogen gas, which is indeed very probable (p. 35). The much smaller amount of nitrates found in the drainage waters where rape cake or farmyard manure are applied illustrates the greater fitness of organic manures for autumn application.

THE DEEP WELL WATERS OF HARPENDEN.

(1) *Incontaminated wells.*—I have now to lay before you some of the results which have been obtained by a study of the drainage water found in the deep wells of the district. Harpenden lies toward the edge of the chalk basin in the middle of which London is situated. The water supply of Harpenden is derived entirely from wells sunk in the chalk, which comes in some places to the surface, and is probably never more than 25 feet beneath it. The water in the wells is in the valley about 60 feet and on the hills about 120–145 feet below the surface. The water level of the district exhibits a rather steep gradient, the underground flow of water being apparently from northwest to southeast. This flow of underground water consists of the mixed drainage of a large area of agricultural land. Following out our previous line of inquiry, it is of great interest to us to ascertain what is the composition of this underground water, the final result of land drainage occurring upon a large scale. We can ascertain the composition of this water from the uncontaminated wells of the district.

In commencing the examination of well waters in a new district the analyst must be cautious in deciding what is truly uncontaminated water. The question will be placed beyond doubt if he examines the water regularly throughout a dry and wet season. Subsoil water at a considerable depth is of a constant composition; any variations perceived in the water of a deep well are due to the admixture of fresh drainage of local origin.

In the uncontaminated wells at Harpenden the proportion of chlorine in the water is practically constant. In one well water, examined every month during two years, the proportion of chlorine varied only from 10.7 to 11.3 per million during the whole period. Eleven per million may be taken as the average proportion of chlorine in the uncontaminated wells of the district. From whence does this chlorine come?

The chlorine present in the rain has been determined for many years at Rothamsted. The average proportion is 2 parts per million.

When rain falls upon the unmanured soils of the drain gauges we have seen that one half of the water is evaporated; we should expect, therefore, that the drainage water which passes through the soil would contain 4 parts of chlorine per million, and this is actually the case.

In the wheat field, where the evaporation is increased by the growth of a crop, the drainage water from the unmanured land contains on an average about 6 parts of chlorine per million. The proportion of chlorine may be still further increased in the still smaller quantity of drainage water obtained from pasture land, but of this we have no certain information. It is difficult, however, to see how the mixed drainage of arable and pasture land, from which the well water is derived, can contain a quantity of chlorine approaching 11 parts per million. The difficulty is still further increased by the fact that chlorine is found in quantity much exceeding 11 per million in the cases of most chalk well waters and springs, including those of undoubted purity. Thus, Dr. E. Frankland in his analyses of one hundred and eleven uncontaminated well and spring waters derived from the chalk, found only seventeen in which the proportion of chlorine was below 15 per million. The facts can, I think, be explained if we may assume that the chalk still contains in its deeper strata some of the common salt, which was undoubtedly among its constituents when it first emerged from the sea. The comparative poverty in chlorides of the chalk waters at Harpenden would then be due to the situation of the wells in an elevated part of the chalk district (344 to 430 feet above the sea). The well waters near the edge of the chalk basin must consist chiefly of filtered rain water, while the water found in the wells of the lower part of the basin must consist largely of the underground drainage from the upper part of the basin, which has percolated through vast masses of chalk during its downward journey. Perhaps the strongest argument in favor of the existence of original chlorides in the chalk is furnished by the composition of the chalk waters obtained from beneath the London clay. Where the chalk has been protected by a thick stratum of impermeable clay, and thus has received no direct washing by rain, the water is found to contain about 150 parts of chlorine per million.

We now turn to the nitrates found in the uncontaminated well waters of the Harpenden district. The average proportion of nitrogen as nitrates in these waters is 4.7 per million; the minimum proportion is 4.4. The proportion of nitrate is not so constant as the proportion of chloride. In the most typical well I have examined it has varied from 4.4 to 5.2 during the year. To understand the cause of this variation, we must remember that every well receives a certain amount of local drainage. Of this local drainage and its effects we shall have striking examples when we speak of contaminated well waters. We have at present to remember that uncontaminated wells receive also a local drainage. The local drainage in the case of uncontaminated wells is free from human sewage, and consequently does not raise the proportion of chlorides in the well water (indeed the chloride generally falls slightly in an uncontaminated well water during the season of greatest drainage), but it always contains nitrates and it may easily contain an

amount of nitric nitrogen exceeding 4.4 per million, the proportion naturally belonging to the underground chalk water. Indeed we have already seen that the uncropped and unmanured soils of the drain gauges yield a drainage water containing an average of 10.5 per million of nitric nitrogen. We shall presently see at what period of the year the effect of local drainage is generally felt.

Before leaving the subject of the uncontaminated wells let me point out to you an important conclusion which follows from the determination of the quantity of nitrates in these waters. The 4.4 of nitric nitrogen per million which the vast reservoir of water in the chalk contains is the final outcome of the drainage of a large area of land under a variety of agricultural conditions. If then we can make an approximate estimate of the amount of water annually percolating through this area, we shall be able to calculate what is the average annual loss which the land suffers by drainage. We may, I think, confidently assert that the average drainage of the district will not exceed 8 inches per annum⁸; this would give an annual loss of 8 pounds, or somewhat less, of nitrogen as nitric acid per acre of land.

The average amount of nitrate contained in uncontaminated spring and well waters in different parts of England is apparently very similar to that found in the good wells at Harpenden. A calculation based on Dr. Frankland's numerous analyses gives an average of 3.8 of nitric nitrogen per million (*Trans. Chem. Soc.*, 1887, 546). If we exclude the low results obtained from spring waters in the oolite, the amount becomes 4 per million. Assuming an average drainage of 8 inches, we have an average loss by drainage of about 7 pounds of nitric nitrogen per acre. This should probably be looked on as below the truth, as no account has been taken of nitrates destroyed by reduction.

(2) *Contaminated wells*.—We now turn to the results shown by the contaminated wells. The contamination in all the cases we shall speak of consisted entirely of fully oxidized matter, neither ammonia nor nitrites being present. The existence of sewage contamination was indicated by the proportion of chlorides and nitrates in the water being above that contained in the pure water of the district.

It requires the coincidence of several conditions to determine the contamination of a well. The water of some old wells placed in a most suspicious neighborhood of urinals and cess pits, was found to be practically uncontaminated, while a well 20 yards off from one of these was largely contaminated. The injury which any source of contamination may inflict on a well is, of course, determined to a great extent by the relation of its position to the direction in which the underground water flows. With a flow of underground water from northwest to southeast it is obvious that any soakage of sewage to the northwest of the well will probably affect its purity, while a similar soakage on the southeast would be nearly harmless.

The old wells of Harpenden are generally steined to a considerable depth with flint, laid in hard mortar or cement; they are thus much better protected against soakage through their walls than the modern wells steined with brick, often used without any cementing material.

The purity of a contaminated well is also largely influenced by the amount of water which is taken from it. The local contaminated drainage is strictly limited in quantity; the underground supply of pure water is practically unlimited in amount; by continuous pumping the proportion of impurity in the well water may thus be greatly diminished.

The amount of chlorides and nitrates varies of course very much in the different wells, according to the extent of the sewage contamination. The chlorine has ranged from 11 (the standard of purity) to 173, the nitric nitrogen from 5 to 44 per million of water.

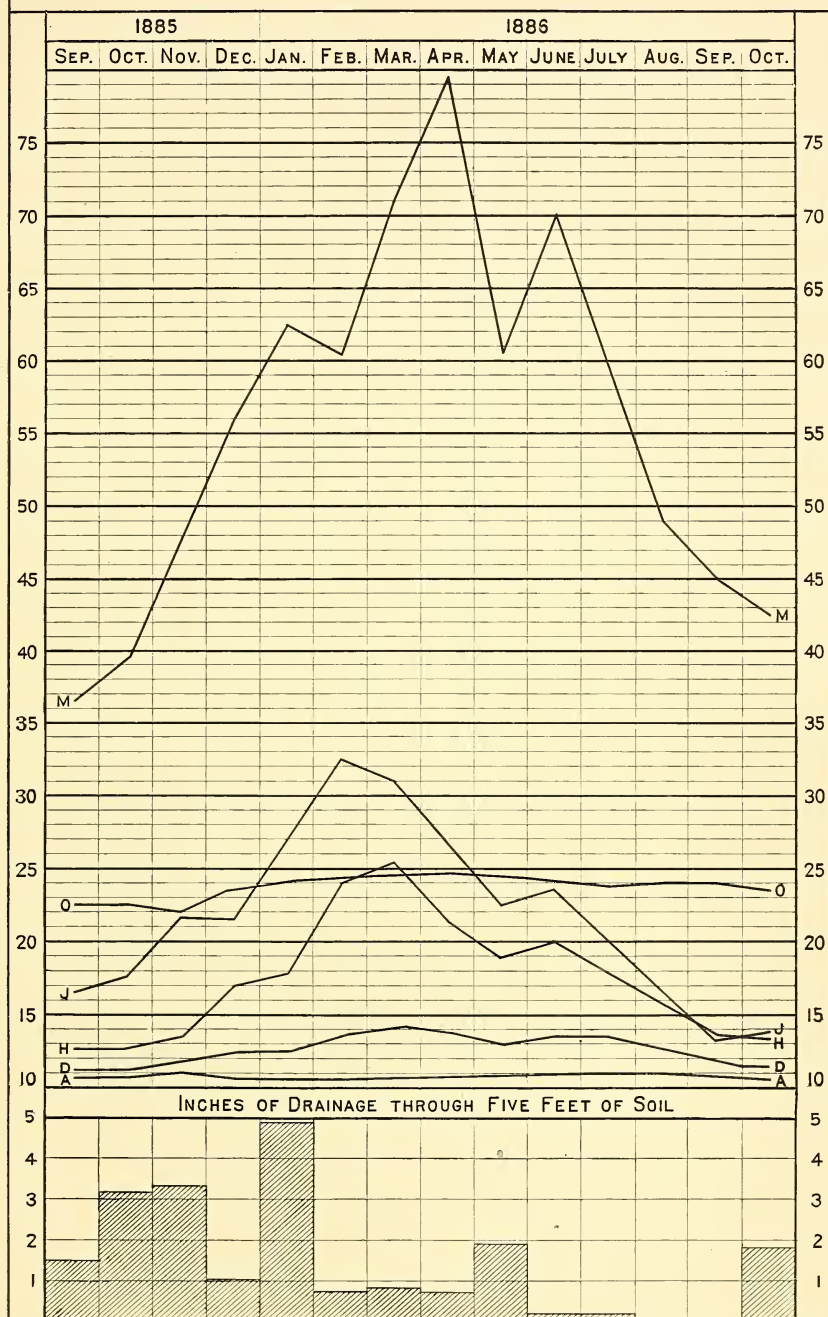
One marked characteristic of all well waters receiving fresh contamination is that the chlorides as well as the nitrates are variable quantities; whereas in a well water not receiving fresh contamination the chlorine is practically a constant quantity throughout the year. This very variable nature of contaminated waters must always be borne in mind by the analyst. A well may contain a nearly pure water at one season of the year, while at another it may be largely contaminated by sewage. A contaminated well is at its best after a long continuance of dry weather; local drainage has then either ceased or been reduced to a minimum. If the proportion of chlorine and nitric acid is still above that proper to the pure underground water, it is because the soil has become saturated with sewage products to a considerable depth.

In different seasons the rise in the impurity of contaminated wells begins at different times, being determined by the amount of rainfall. We have seen in the results shown by the drain gauges, that considerable drainage generally commences in October and continues till the end of February. This is what occurs in an average of seasons. In a season of this average or normal character, a considerable rise in impurity will be found in the Harpenden wells by the end of November. It requires two consecutive months of active drainage to start the local percolation into the wells. Winters in which wet and dry months alternate have only a small effect on the well waters. The rise in impurity is greatest when drainage is maintained continuously during three or four months. When once the soil has become saturated the effect of any heavy rain is sure to appear in the well waters, but usually about one month after the rain has occurred.

That the increase in chlorides and nitrates is due to a purely local percolation, is illustrated by the fact that bad wells have considerably increased in impurity before the water level in the well begins to rise. The impurity doubtless enters the well through channels opening into its side. The rise in level of the underground water does not begin, in a normal season, till January.

HARPENDEN WELL WATERS

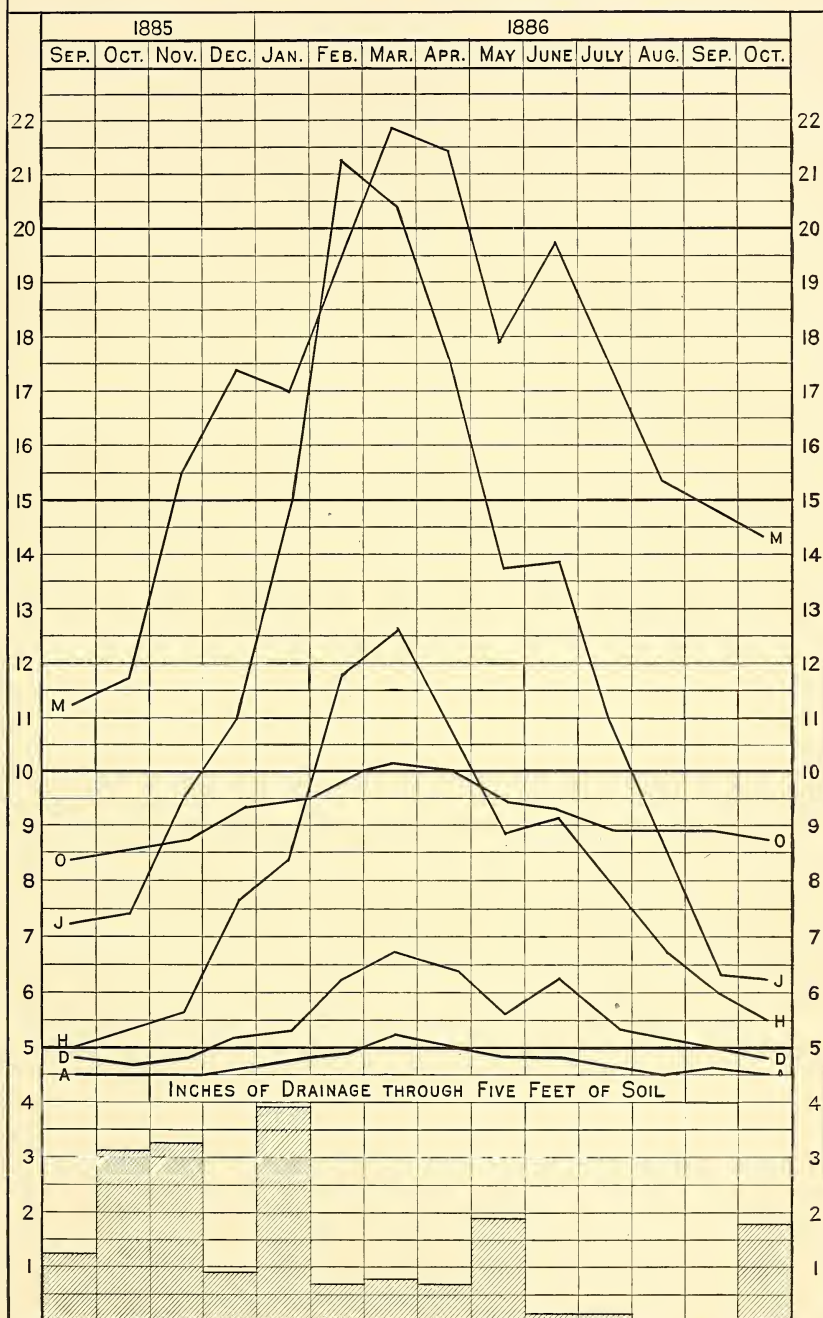
CHLORINE—PARTS PER MILLION

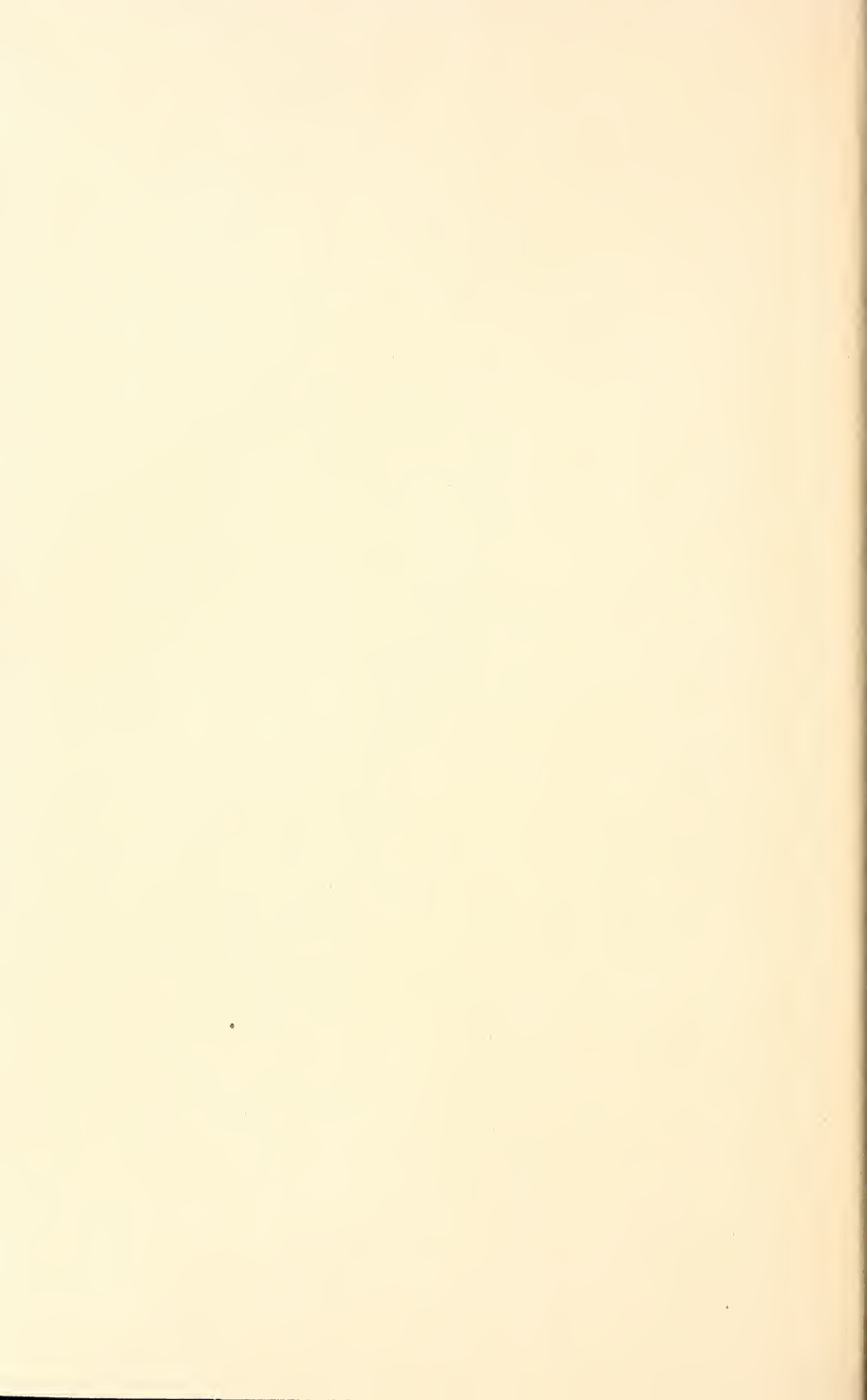




HARPENDEN WELL WATERS

NITROGEN AS NITRATES—PARTS PER MILLION





The two charts (Plates X and XI) before you will give you a better idea than any figures of the course of change in the proportion of chlorides and nitrates which may take place in a well water in the course of a single season. The waters of eleven selected wells were analyzed every month for two years, and some of them for a longer period. The results given by six of these wells are depicted in the charts. The season chosen is that of 1885-86, which was a fairly normal one.

At the bottom of each chart is a series of short columns showing the amount of water passing each month through 5 feet of soil in the drain gauge. This percolation through the soil is the motive power carrying chlorides and nitrates into the contaminated wells. The lowest line, that belonging to well A, exhibits the course of change, or rather the absence of change, in the water of an uncontaminated well. Wells D, H, and J are all distinctly contaminated during the height of the drainage season, but after several months of dry weather the chlorides and nitrates fall almost to the quantities found in the pure waters. Well M is far more highly polluted and its water remains, even after a long continuance of dry weather, far removed from the standards of purity. You will see that the effect of each fresh amount of drainage is very conspicuous in the case of the polluted wells; the effect is, however, always perceived the month following that in which the drainage occurred; thus the pause in the drainage during the month of December is reflected by the composition of the well waters in January, while the abundant January drainage sends up the chlorides and nitrates in February. The effect of the drainage in May upon the waters in June is very manifest.

Well O is curiously different from all the others; its water contains about twice as much chlorine and nitric acid as the water of pure wells, but these chlorides and nitrates are, like those of the pure wells, practically constant quantities and remain almost unaffected by seasons of drainage or drouth. This well is the more modern of the two wells at Rothamsted; it is probably about two hundred years old. For many years it was surrounded by farm buildings and liable to considerable contamination. About thirty years ago these sources of contamination were removed. The surface soil in the neighborhood has now become purified, and the autumn and winter drainage bring no fresh contamination into the well. The subsoil still, however, contains an excess of chlorides and nitrates and maintains the somewhat high proportion of these salts in the water.

The proportion of chlorides to nitrates varies a great deal in different well waters, some wells are characteristically chlorinous and others as decidedly nitric. The average proportion of chlorine to nitric nitrogen in the water of the pure wells is 100:43, but in individual contaminated wells the average has varied from 100:25.6 to 100:55.5.

This wide difference in the proportion of chlorine to nitrogen is apparently caused by the nature and age of the contamination. Chlorides, as we all know, have their principal origin in the common salt consumed

in human diet. When in place of contamination by human sewage we have contamination by drainage from stables, the common salt is absent and the well water becomes strongly nitric in character. The proportion of chlorine to nitrogen in human sewage will also vary considerably with the character of the diet which gives rise to it. The sewage from poor cottages, where salt bacon and herrings are the only meat consumed, will be far more chlorinous than the sewage from houses containing a well-fed population. The sewage of house drains will again be more chlorinous than the sewage from cess pits. A considerable increase in the proportion of chlorine to nitrogen will also be brought about where the well is surrounded by vegetation, as plants will consume the nitrates in much larger quantity than the chlorides. Thus the average proportion of chlorine to nitric nitrogen is 100:276 in the drainage water from the 60-inch, uncropped drain gauge, but about 100:55 in the drainage water from the unmanured plot in the wheat field. Wells suffering chiefly from old contamination are generally chlorinous; the chlorides are indeed indestructible, while the nitrates may be diminished both by assimilation and reduction.

The proportion of chlorine to nitrogen is generally not constant throughout the year. This is true, to a limited extent, in the case of the pure wells. We have, indeed, already remarked that while the chlorine remains constant or slightly falls during the season of local drainage, the nitrates rise to a small extent. Thus the proportion of chlorine to nitrogen in the water of the uncontaminated well A has varied from about 100:40 to 100:48, the greater proportion of nitrates occurring in March. In the case of contaminated wells there is generally a far greater rise in the proportion of nitrates. Thus the water of well J contained 100 of chlorine to 41.6 of nitric nitrogen in October, 1885, and 100:66.8 in the following March. The proportion fell again to 100:41.7 in December and rose to 100:64.5 in March, 1887. The proportion in the water of well L rose from 100:35.5 in September, 1885, to 100:58 in February, 1886; and from 100:41.4 in September, 1886, to 100:53.4 in February, 1887. The great rise in nitrates generally occurs rather suddenly after two or three months of active drainage.

The facts which determine this alteration in the proportion of chlorides and nitrates have already been mentioned. You have already seen (Table XIV) the great alterations which occur in the composition of the drainage water where ammonium chloride has been applied to the soil; the chlorine passes at once freely away, while the ammonia is detained and the nitrates which result from its oxidation make their appearance at a later period. A similar series of changes occurs when sewage mixes with the soil. In chlorinous wells and in wells suffering merely from old contamination, no marked alteration in the proportion of chlorine to nitrogen occurs.

(3) *Mineral constituents of the waters.*—But little has been done to ascertain the detailed composition of the pure and polluted waters;

doubtless much interesting information would be afforded by a study of their variations in composition throughout the year. I am able, however, to lay before you a partial analysis of three of the waters, the uncontaminated well A, the nitric well J, and the chlorinous well M. The samples were taken for analysis in February, 1886, at a period of maximum impurity.

TABLE XVIII.—*Composition of uncontaminated and contaminated deep well waters, collected February, 1886, in parts per million.*

	Incontaminated.	Contaminated.	
	Well A.	Well J.	Well M.
Lime	158.0	211.0	220.0
Magnesia	4.1	9.7	10.5
Carbonic anhydride	118.7	130.6	124.2
Sulphuric anhydride	3.8	28.5	15.8
Nitric anhydride	18.9	82.2	74.4
Chlorine	10.7	32.7	71.0
Silica	17.6	15.8	15.4
Undetermined	15.8	49.5	68.1
Total solids	347.6	560.0	599.4

Looking at the figures in Table XVIII we see that there is a much larger quantity of dissolved matter in the polluted than in the pure waters. The proportion of silica shows no rise with pollution; the proportion of carbonates shows a very small rise. On the other hand the amount of lime, and still more of magnesia, present in the waters receiving sewage contamination, is much increased. The rise in the chlorides and nitrates is very notable, but this part of the subject has been fully discussed. The great rise in the proportion of sulphates is, however, a fact which we have not yet noticed; it is greatest in the nitric well J, a circumstance which certainly suggests the thought that both nitrates and sulphates are originally derived from the albuminoids of food. The undetermined matter will consist in part of alkalis; these were undoubtedly present, as the total acids were in all cases in excess of the lime and magnesia determined. Calculating from this datum, it would appear that the quantity of alkalis in the contaminated waters was three or four times as great as in the uncontaminated; the alkali present was probably soda.

The quantity of sulphuric acid in the pure well water appeared so remarkably small that a second determination was made later in the year, using two liters of water for the experiment; the amount of sulphuric anhydride obtained was, however, only 2.75 per million. This amount is scarcely more than that found on an average in the Rothamsted rain, namely, 2.52 per million. As the rain water is concentrated to at least one third before it appears as drainage in the well, it is evident that a considerable part of the sulphates in the rain has been retained by the soil or appropriated by the vegetation growing upon it.

In closing my lectures I must thank you for the very kind manner in which you have received my endeavor to tell you something about the Rothamsted experiments. I am well aware that my lectures have been highly technical, and that to any person not specially interested in the subjects treated of they must have been extremely dry and unattractive. I should not have ventured to go so much into detail if I had not had the privilege of lecturing to a special audience. In speaking to the representatives of the American agricultural colleges and experiment stations I have felt that I might assume in my hearers a real interest in the methods and details of agricultural investigations, even when these investigations dealt with problems which are at present foreign to American agriculture. If I have made too great a demand upon your patience you must forgive me.

Let me conclude by wishing God speed to the American experiment stations. You have, I believe, at the present time in your country more than fifty stations, each of them endowed with an income equal or surpassing that possessed by Rothamsted. We have in England one station; you have more than fifty. What a great future lies before you! But if at the end of fifty years each of your stations is to show a record of work done equaling or surpassing that accomplished by the old station in England, it will only be, I think, by each pursuing its work in the same spirit of accuracy, thoroughness, and patience which has characterized the Rothamsted experiments.

LIST OF ROTHAMSTED PAPERS REFERRED TO IN THE PRECEDING LECTURES.

- On Nitrification.—*Jour. Chem. Soc.*, 1878, 44.
- On Nitrification, part II.—*Trans. Chem. Soc.*, 1879, 429.
- On the Determination of Nitric Acid by Means of Indigo, with Special Reference to Water Analysis.—*Trans. Chem. Soc.*, 1879, 578.
- Note on the Appearance of Nitrous Acid during the Evaporation of Water.—*Trans. Chem. Soc.*, 1881, 229.
- On Alterations in the Properties of the Nitric Ferment by Cultivation.—*Report British Association for the Advancement of Science*, 1881, 593.
- Letters on Fertility.—*Agricultural Gazette*, February-May, 1881.
- On the Amount and Composition of the Rain and Drainage Waters Collected at Rothamsted.—*Jour. Roy. Agr. Soc.*, 1881, 241, 311; 1882, 1.
- On the Determination of Nitric Acid by Means of its Reaction with Ferrous Salts, part I.—*Trans. Chem. Soc.*, 1880, 468; part II, *ibid.*, 1882, 345.
- On the Determination of Nitric Acid in Soils.—*Trans. Chem. Soc.*, 1882, 351.
- Determinations of Nitrogen in the Soils of some of the Experimental Fields at Rothamsted, and the Bearing of the Results on the Question of the Sources of the Nitrogen of our Crops.—*Report American Association for the Advancement of Science*, 1882.
- Contribution to the Chemistry of Fairy Rings.—*Trans. Chem. Soc.*, 1883, 268.
- New Determinations of Ammonia, Chlorine, and Sulphuric Acid in the Rain Water Collected at Rothamsted.—*Jour. Roy. Agr. Soc.*, 1883, 313.
- The Nitrogen as Nitric Acid in the Soils and Subsoils of some of the Fields at Rothamsted.—*Jour. Roy. Agr. Soc.*, 1883, 331.
- On Nitrification, part III.—*Trans. Chem. Soc.*, 1884, 937.
- On the Action of Gypsum in Promoting Nitrification.—*Trans. Chem. Soc.*, 1885, 758.
- On some Points in the Composition of Soils, with Results Illustrating the Sources of the Fertility of Manitoba Prairie Soils.—*Trans. Chem. Soc.*, 1885, 380.
- On the Distribution of the Nitrifying Organisms in the Soil.—*Trans. Chem. Soc.*, 1887, 118.
- A Contribution to the Study of Well Waters.—*Trans. Chem. Soc.*, 1887, 500.
- The Chemical Actions of some Microorganisms.—*Trans. Chem. Soc.*, 1888, 727.
- On the Present Position of the Question of the Sources of the Nitrogen of Vegetation, with some New Results and Preliminary Notice of New Lines of Investigation.—*Phil. Trans. Roy. Soc.*, 1889, B. 1.
- The History of a Field Newly Laid Down to Permanent Grass.—*Jour. Roy. Agr. Soc.*, 1889.
- The Amount of Nitric Acid in the Rain Water at Rothamsted, with Notes on the Analysis of Rain Water.—*Trans. Chem. Soc.*, 1889, 537.
- On Nitrification, part IV.—*Trans. Chem. Soc.*, 1891, 484.

